Biomechanical Knee Joint for Exoskeleton
Final Design Review

Prepared for: The Lower Limb Exoskeleton Assist Project

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Statement of Disclaimer

Abstract

Our senior design project consisted of designing and manufacturing a biomechanically accurate, actuated knee joint to be integrated into an exoskeleton being developed by the Lower Limb Exoskeleton Assist Project (LLEAP), a part of the EMPOWER student association at Cal Poly, San Luis Obispo. As the human knee flexes and extends throughout gait motion, the center of rotation changes. Currently marketed exoskeletons have one point of rotation, which over constrains the knee and causes misalignment between the user and the suit [1]. Our goal was to mimic natural knee joint motion by changing the center or rotation, thus reducing misalignment and limiting power loss. We designed this knee joint for our prospective exoskeleton user: Carlo Ruggiero, a 21-year-old Cal Poly student with a complete C8 injury to his spine which resulted in loss of function and sensation from his chest and below.

Our design consists of a linear actuator mounted along the outside of the user's thigh, which drives a four-bar linkage in line with the user's knee. After manufacturing and testing our design, it was found that the joint met the necessary power requirements and reached the required angles for human gait. However, the linear actuator that was purchased was too long to fit properly on the user's leg and is unable to vary its speed.

This verification prototype proves that mimicking knee joint motion for exoskeleton applications is feasible but requires integration of a linear actuator with greater power density and the ability for speed control. We also recommend using biomedical imaging to accurately determine the center of rotation throughout actuation. This would allow for tuning of the lengths of the links in the four-bar linkage to match the user's knee biomechanics more precisely.

Contents

1 Introduction

Our team consists of mechanical and biomedical engineering seniors at California Polytechnic State University, San Luis Obispo. The project is funded by the TECHE (Transforming Engineers Through Community Hands-on Engagement) lab, and the sponsor for our project is Dr. Eric Espinoza-Wade, who has expertise in dynamic systems analysis and control systems engineering for health science. The main objective of this project is to develop a knee joint for the exoskeleton being developed by the Lower-Limb Exoskeleton Assist Project (LLEAP), which is part of the Cal Poly EMPOWER club, to be used by Carlo Ruggiero, a student at Cal Poly who is paralyzed from the chest down. The original requirements specified by the club are:

- The joint must be biomechanically accurate (i.e., must match the natural roll-glide movement of the knee joint).
- The design must be lighter than the earlier LLEAP prototype (under 20 lb.).
- The knee joint must be compatible with their exoskeleton design.
- The joint must withstand the loads of the user and suit while walking.

Within this report, we summarize our finalized design, including a description of our final design and all design changes we have made since our Critical Design Review (CDR). We then discuss the implementation of our design, including procurement of materials, manufacturing, assembly, and software and electronics, followed by the lessons we learned throughout this process. Next, we discuss the design verification process, including our specifications and testing that was carried out, along with the test results. Lastly, we discuss our experiences while working on this project, as well as recommendations and next steps for the design.

2 Design Overview

Since CDR, we have implemented design changes to address hip design changes by LLEAP, tolerancing issues, and manufacturing issues. For each of these alterations, we completed analysis to support the decisions and ensure failure would not occur during use. These changes, as well as descriptions of both the design and its functionality, are detailed below.

2.1 Design Description

Our joint consists of a four-bar linkage tuned to mimic the natural roll-glide motion of the human knee, powered by a linear actuator (Thomson Linear LL24B040-0100LEXANNSD). The linear actuator is attached to the femur structure and actuates the joint by exerting a force on the aluminum coupler below the tibia link, resulting in a moment about the joint. This moment causes the four-bar linkage to rotate, thereby moving the lower leg portion of the exoskeleton. The overall design is approximately 18 inches tall (when joint is at the 90-degree/fully retracted position), 7.5 inches deep (measuring from the front of the frontal support structure to the back of the linear actuator), and 4 inches wide (from the exterior to interior of the support structure). See Figures 1-3 below for connection locations and knee joint structure.

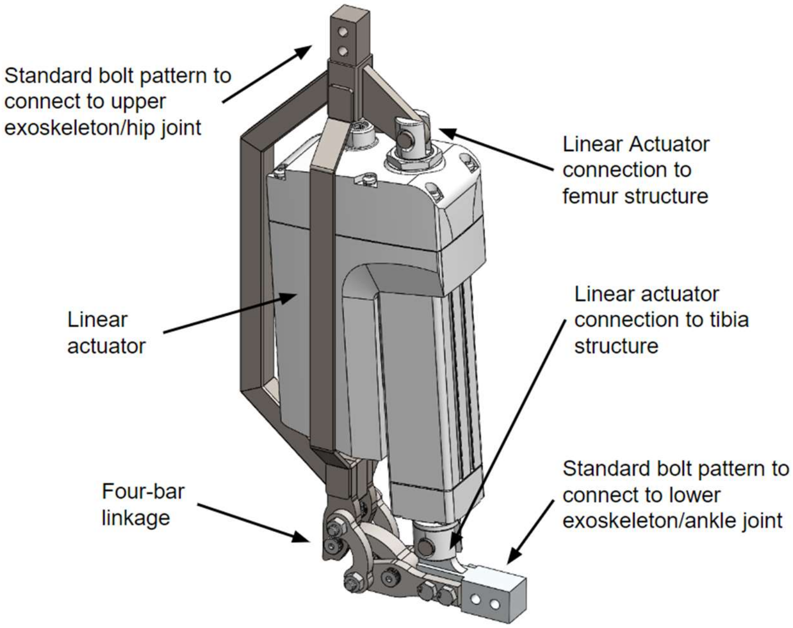


Figure 1. Interior lateral view of knee joint.

To create the lateral and frontal linear actuator support structure, we used mitered square tubing welded at 130˚ and 135˚ angles. We bent the inner soft goods connection support (shown in the center of Figure 1) into shape then welded it with the lateral and frontal structures at the femur structure tube (top) and femur structure spacer (bottom) connection points. Figure 2 shows the lateral support structure.

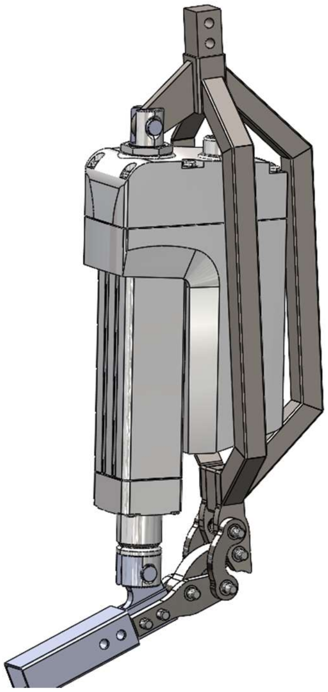


Figure 2. Exterior lateral view of knee joint assembly.

2.2 Design Function

Figure 3 shows a detailed view of the four-bar linkage. It consists of four links: the femur, tibia, anterior cruciate ligament (ACL), and posterior cruciate ligament (PCL), each curved to avoid collisions with the linkage fasteners. Hard stops are included on the femur links to prevent hyperextension of the knee by providing a matching profile for the tibia links; through this geometry, the femur links "catch" the tibia link when the joint is extended to 180-degrees, stopping the motion of the lower leg. The functionality of these hard stops can be seen when the knee joint is fully extended, shown below in Figure 4. The linear actuator is positioned so it will bottom out when the joint is fully retracted, preventing over-flexion of the user's knee. The center of rotation of the joint is located at the intersection of the ACL and PCL centerlines and, as gait motion is initiated by the user, changes through time, mimicking human knee joint biomechanics. The link lengths and positions are critical for accurately imitating human knee motion, which varies for every person. The link lengths we used were based off a four-bar linkage patent for mimicking knee joint motion [2]. Each connection between the links is supported by a press-fit needle bearing and a high-strength precision steel pin constrained with retaining rings (originally shoulder bolts with lock nuts). The needle bearings allow for smooth actuation under high loads and the steel pins have precision diameters that interact with the bearings and hold the links together.

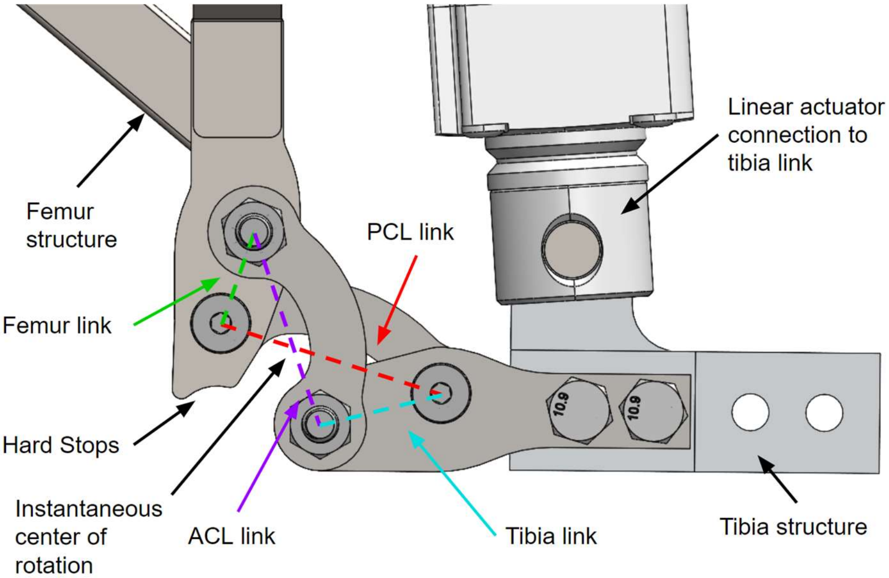


Figure 3. Detailed view of the four-bar linkage.

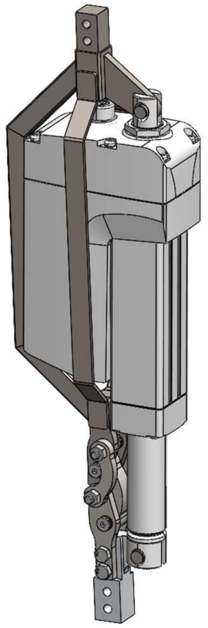


Figure 4. Fully extended knee joint assembly.

The linear actuator is controlled using a P-controller and is powered by an external battery. This linear actuator was selected based on calculated force, speed, stroke length, and duty cycle values. The weight, length, voltage, and price were also considered to optimize the motor performance and minimize its size and weight while remaining under budget. The actuator must weigh less than 15 pounds for the suit to be an ideal weight. The fully retracted length of the actuator must be less than 14 inches to allow for the entire assembly to fit on the user's 18-inch-long femur. The linear actuator that was chosen can be seen in Figure 4.

To control the actuator, two sets of wires run up the front of the linear actuator to just under the femur connection to the hip component. While there may be room to place the electronic components there between the linear actuator support structure and actuator itself, our current plan is to run wires up through the leg structure designed by another LLEAP senior project in the Biomedical Engineering department. All electronics will be located in the back structure connected to the user's torso, where the battery and all other electronics will be housed.

To connect the actuator to the structure, an additional steel plate was welded to the top of the structure and connected to the linear actuator with a precision pin, secured with retaining rings. Figure 5 shows a close-up of the connection between the linear actuator, the femur structure from the linkage, and the femur connection to the hip joint. A through-hole at the top of the linear actuator allows it to be bolted to the top metal link (linear actuator connection to femur). The lower tibia linear actuator connects to the middle of a fork-shaped linear actuator rod end. M8 bolts are used to connect this lower tibia linear actuator aluminum coupler to the tibia link. This connector also has a standard bolt pattern at the output to the ankle that will accept a square tube fastened by M8 bolts (Figure 3).

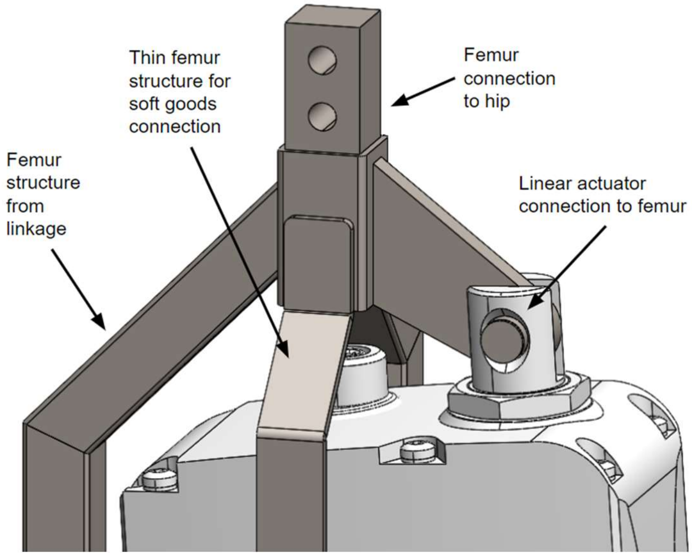


Figure 5. Top connection to the linear actuator (original design).

The steel tube structure connects the top of the linear actuator and the femur connection to the four-bar linkage. This structure conforms around the linear actuator's geometry through welded angled square steel tubing. There is also a thinner, non-structural, bent rectangular steel bar stock plate (soft goods connection) that is welded to the structure on the inner side of the assembly. The joint will connect to the user with straps and soft goods (developed by another LLEAP senior project through the Biomedical Engineering department) that minimize misalignment and prevent injury.

The process of actuating the knee joint involves a control system and electronic setup detailed in the user manual in Appendix A. The joint can be very dangerous due to the high forces applied by the linear actuator and many pinch points, but we completed a detailed risk assessment in Appendix B to ensure that we considered all these dangers.

2.3 Design Changes Since CDR

The components connecting our design to the other exoskeleton components have changed slightly since CDR. The knee joint was previously connected to the cycloidal hip joint, but due to changes in the LLEAP hip team's design and manufacturing capabilities, their design will not be completed until Fall of 2023. Therefore, for this year's verification prototype, the previous planetary hip design was used in the exoskeleton assembly. This changed the connection to the hip joint, and the new connection is shown below in Figure 6 (compared to the original connection seen above in Figure 5). A plate was welded to the steel bar stock, with holes that interface with the output of the hip joint.

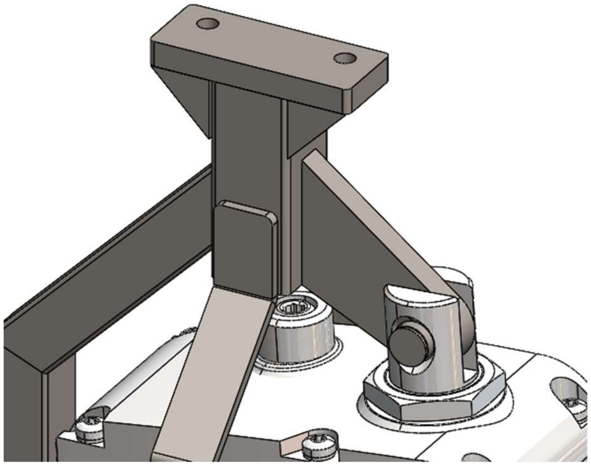


Figure 6. New femur connection to hip.

The linkage design has also changed slightly. After receiving the shoulder bolts that were intended to fit inside the needle roller bearings for the linkage, we realized that the tolerance of the outer diameter of the shoulder bolts was not tight enough and the fit between the bolts and the bearings was very loose. This would have introduced significant backlash and instability in the linkage, so to fix this, we ordered precision shafts with the correct outer diameter and improved tolerancing to fit in the bearings. These shafts were turned on the lathe and utilize retaining rings to keep them in place. The original linkage assembly with shoulder bolts is shown in Figure 7 below. The new linkage assembly with shafts and retaining rings is shown in Figure 8.

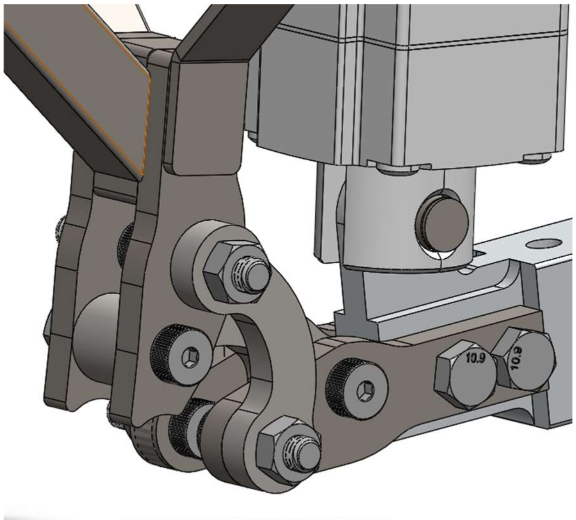


Figure 7. Original shoulder bolt and nut design.

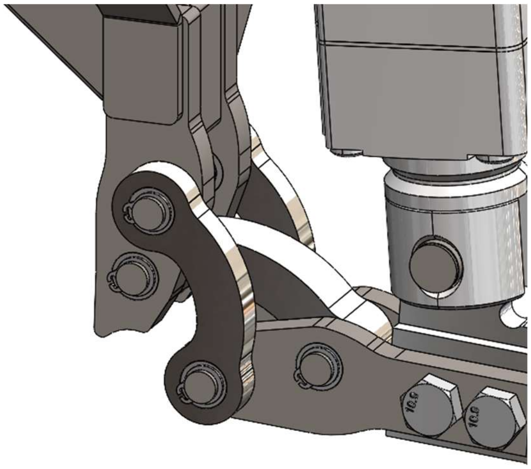


Figure 8. New shaft and retaining ring design.

During the milling process for the aluminum coupler, we mistakenly neglected a critical fillet, which resulted in an increased stress concentration and the coupler being unable to withstand the applied loads when modeled in FEA. Figure 9 shows the intended shape of the aluminum coupler. To correct this, we drilled a hole at the site of the corner, seen in Figure 10, to reduce the peak stress in the stress concentration. Before implementing this, however, we re-ran the FEA simulation with the fix and an extreme loading case with a safety factor of 1.4, shown in Figure 11. After completing this simulation, the maximum stress was confirmed to be well below the yield strength, and therefore we added the hole to the aluminum coupler to address the mistake.

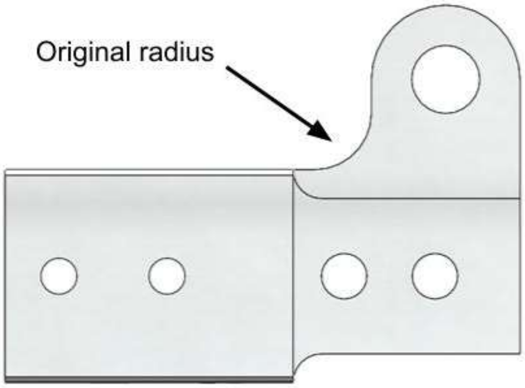


Figure 9. Original aluminum coupler with fillet.

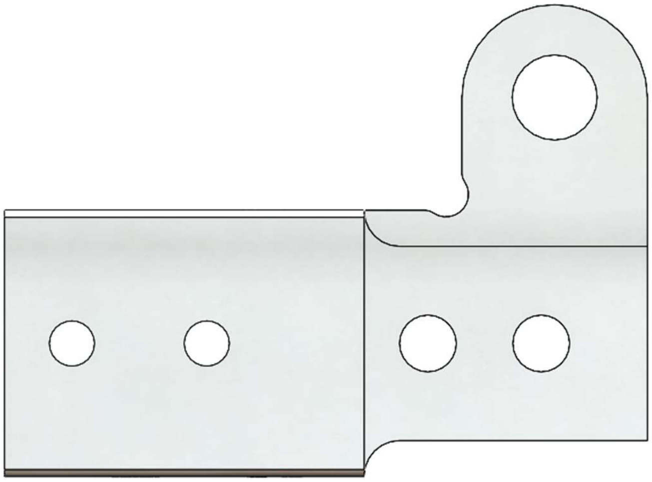


Figure 10. Aluminum coupler with stress concentration relief after manufacturing error.

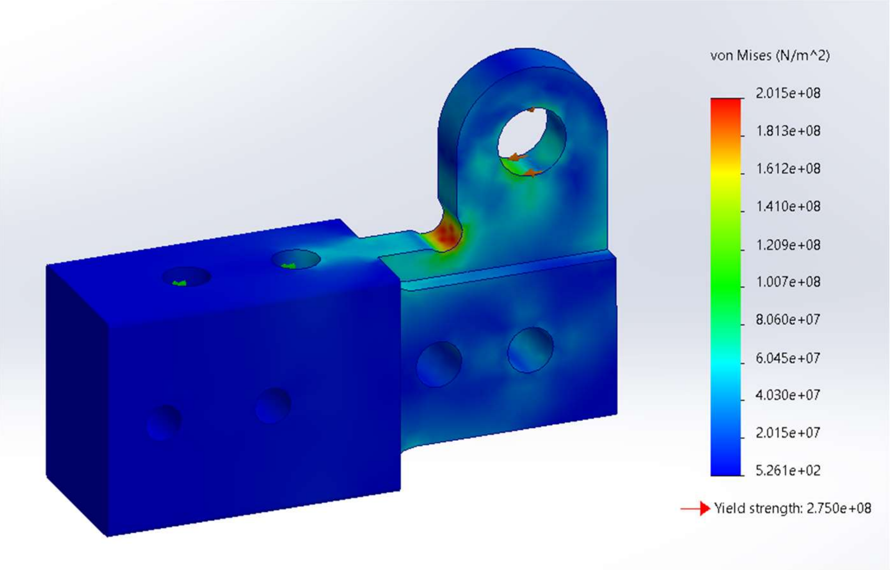


Figure 11. Finite element stress results for stress concentration relief.

3 Implementation

After finishing our design, we began procuring materials from online sources such as McMaster-Carr and began manufacturing in the Cal Poly on-campus machine shops. This section details our manufacturing process, assembly process, and the electronics and wiring schematics.

3.1 Procurement

We obtained most materials and components for the knee joint through a third-party supplier, McMaster-Carr. The linear actuator was purchased directly from the Thomson Linear website. All materials were purchased using the funds acquired through the Cal Poly TECHE Lab. TECHE provided the materials for the aluminum coupler, which is in the lab in building 192, room 130 (192-130) at Cal Poly.

Lead times had a large influence on this manufacturing plan, as the Thomson linear actuator had a 55-business day lead time. Most manufacturing steps were completed prior to the actuator's arrival, and then the final assembly was completed upon arrival. Throughout the lag time, we were in constant communication with the adjacent mechanical design teams and mechatronics team to ensure the delay did not affect any team's design progress.

Limited shop resources were considered in our manufacturing timeline. As shown in our step-by-step plan, we used high-demand machining equipment, such as the mill and lathe, extensively in our manufacturing process. To prevent backlogs from significantly delaying our timeline, we began machining components that required this equipment early on and were largely able to account for lack of availability.

3.2 Component manufacturing

We milled the lower aluminum coupler, shown in Figure 10, out of aluminum stock at the Cal Poly machine shops. We began manufacturing the links by using the water jet to cut each profile out of an 8-mm-thick steel plate and located their respective pin holes during the same operation. The post-water jet links can be seen in Figure 12. Next, we began the process of drilling and reaming the precision holes to press-fit the needle roller bearings. Due to the complex geometry of the links, we needed to utilize soft jaws to create flat surfaces to clamp into the vise of a mill. Using the component models in SOLIDWORKS, we created 3D-printed fixtures for each link in the four-bar linkage. We printed each fixture using PLA and designed the fixtures to envelope the profile of their respective links, creating a rectangular outline around the links so that they fit parallel and square in the vise of a mill.

Figure 12. Water jetted links and linear actuator connections.

When manufacturing the upper femur connection, which can be seen on the right side of Figure 12, we mistakenly welded two of them together to make the connection 16-mm thick before realizing that it only needed to be 8-mm thick, so that component had to be cut on the water jet again before we could remake it. However, when attempting to make the part properly, we used the incorrect drill bit size and had to get the same part cut on the water jet for a third time before we successfully manufactured it.

To drill and ream the precision holes required for a proper press fit of the bearings, we first clamped each link in its respective soft jaw in the mill vise, ensuring the surface of the part is level by tapping with a rubber mallet as the vise compresses the part. Then, we located the center of one of the pilot holes for the pin holes using an edge finder. To do this, we first zeroed the y-axis position by finding the top and bottom edge of the hole and positioning the mill in between these two measurements. We then zeroed the x-axis position by repeating this process in the x-direction. Next, we exchanged the edge finder for a 29/64" drill bit, drilled through the hole, and then reamed the hole using a 12-mm reamer. We then moved the mill over the next hole using the dimensions specified in the drawing file and repeated the drilling and reaming process.

While we were able to manufacture each part within our tolerance limits using this process, we did find that the locator holes (made using the water jet) were slightly off in their position, which introduced uncertainty into the design as seen in Figure 13. Although this was not ideal, we accounted for it by ensuring that the critical dimension–the distance between the pin holes (if more than one is necessary)–was used rather than locating off the second hole in the same manner as the first with the edge finder.

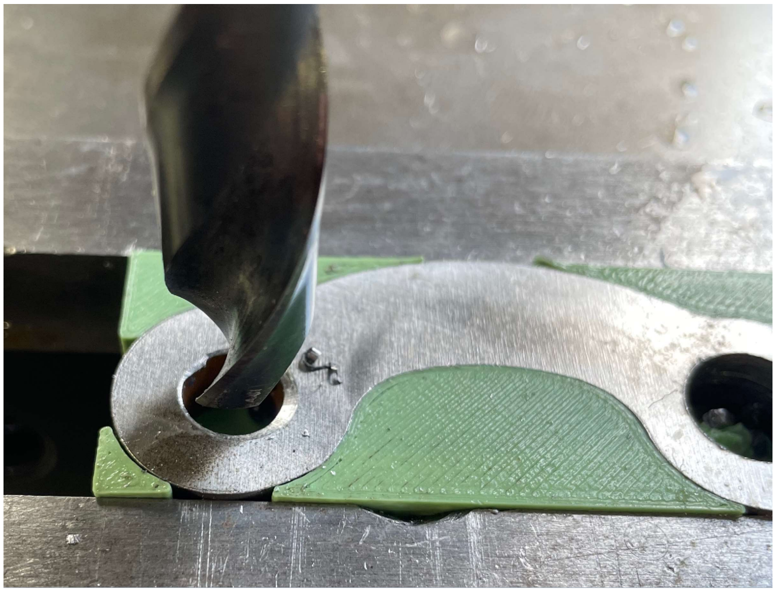


Figure 13. ACL link in 3D-printed soft jaw.

After reaming each link's pin holes to the correct diameter, we pressed the 12-mm external diameter needle roller bearings into each hole using a vise and a soft cloth to prevent damage to the bearing housings. The only challenge during this step was ensuring the bearings were fully pressed in so they did not stick out and the linkage fit together properly.

We rough-cut the steel tubes surrounding the linear actuator to their approximate angles using a protractor and the steel abrasive saw, then ground to the correct final angles using the disk sander. To weld the structural tubes at the correct angles, we created a wooden jig, which is shown in Figure 14. Some of the angles were slightly off, within a tolerance of less than 3 degrees, which was accounted for by filling the gaps when welding.

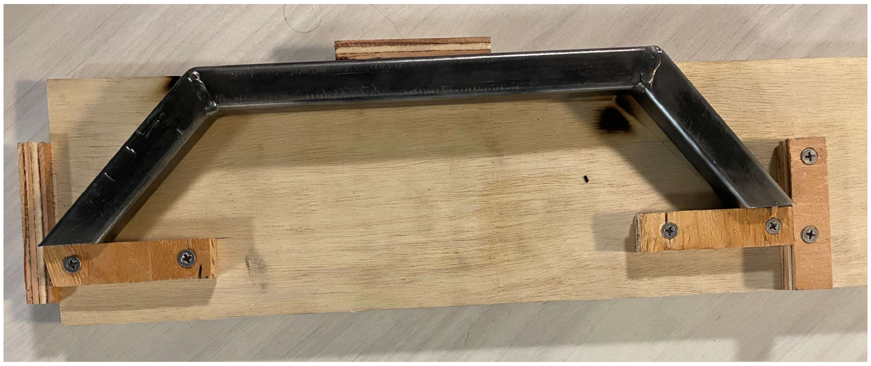


Figure 14. Wooden welding jig.

We performed all welding for the structure using a TIG welder. One of the largest setbacks during manufacturing was the availability of welders, with the problem exacerbated by the fact that one of the TIG welders was taken out of the machine shop for use by another club and was never returned.

In addition to the structural tubes, we bent the soft goods connection bar by measuring the locations of the bends and using a hammer and vise to bend to the proper angles. We verified the angles using a protractor to ensure the connection bar would fit well. This component was then welded to the rest of the structure. Lastly, following the design change for the femur connection to the hip, we welded the hip connection tab and supports to the femur coupler.

To manufacture the pins for attaching the linear actuator and connecting the links, we turned round steel stock on the lathe. Figure 15 shows the pins and retaining rings used to hold the links together. We needed a custom tool to create the grooves in the pins for the retaining rings, so we ground high-speed steel blanks into cutting tools with the correct thickness. We used these cutting tools to turn the grooves for the retaining rings and then used a parting tool to cut the pins to the correct lengths. We repeated this process for all pins including those used for the linear actuator attachment.

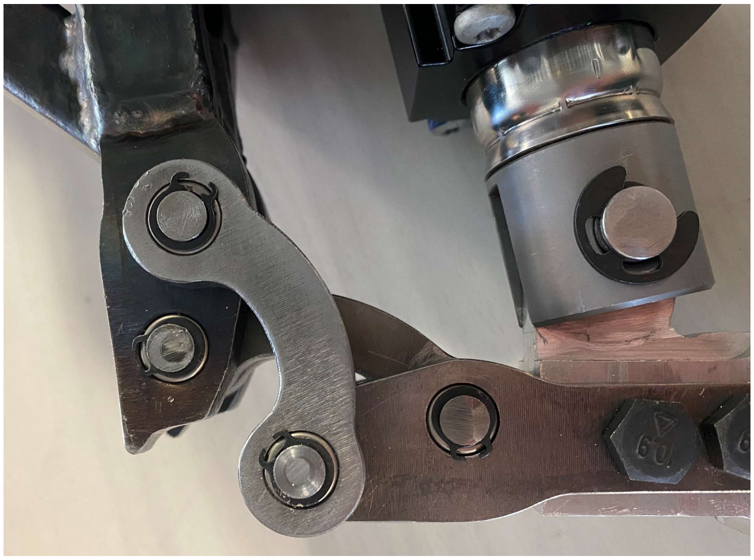


Figure 15. Knee joint with pins and retaining rings.

3.3 Assembly

We assembled the linkage by press-fitting the needle roller bearings into the reamed holes in the links. We installed one retaining ring onto each precision shaft, then began assembling the linkage by inserting the pin into each link in the correct sequence until the full linkage was assembled. Next, we installed the second retaining ring onto each shaft to fully assemble the linkage. Then, we bolted the tibia links to the aluminum coupler using M8 bolts and used a pin to attach the lower linear actuator mounting hole to the aluminum coupler. We used another pin to attach the upper linear actuator mounting hole to the top of the knee joint. Retaining rings were fitted to each pin constraining the linear actuator. This was the final assembly step for the manufactured knee joint, which allowed us to move forward with controlling the prototype.

3.4 Software & Electronics

While most of the control system will be completed by the mechatronics team in the LLEAP club, our team used an ESP32 board connected to an angular potentiometer to track angular position of the joint and used this data to control the joint and for our tests. The potentiometer was attached to the joint using a 3D-printed mount shown in red in Figure 16. These electronics were the final components we purchased, and the detailed final budget summary table is attached in Appendix C.

Using the feedback from the potentiometer, we were able to create a basic P controller for the knee joint. In this scheme, an angle is input into the system and is then compared to the current angular reading of the potentiometer (converted from an output voltage to an angular reading through a gain developed from calibration and the ESP32 datasheet). The linear actuator will then extend or retract (depending on the current and input angles) until it is within 0.5% of the input angle. A tolerance around the input angle rather than the angle itself was used because of the limited accuracy of the potentiometer and noise in the wiring system. Appendix F has the complete controller code used to actuate the knee joint.

Figure 16 (below) depicts the hardware setup to control the knee joint. In this scheme, the wires for controlling the extension and retraction of the actuator (wires 6 and 7, respectively) are each connected to a GPIO pin of the ESP32 through a 2N2222A transistor (acting as a switch). The angular potentiometer (blue component fixed to the red, 3D-printed components) is connected to the ESP32 5V output, GND, and GPIO pins. The input voltage for the linear actuator – as well as logic voltage for its extend and retract switches – is connected to a switching regulator (component in upper left portion of image) which allowed us to step the battery (not pictured) voltage down to the desired value of 24V. There are also break resistors (gold components) connected as specified in the electronics datasheet of the actuator (all shown in Figure 16). Figure 17 shows the complete wiring diagram for the linear actuator.

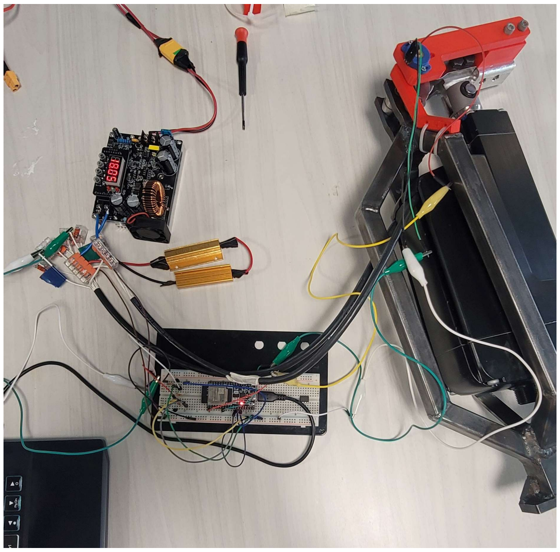
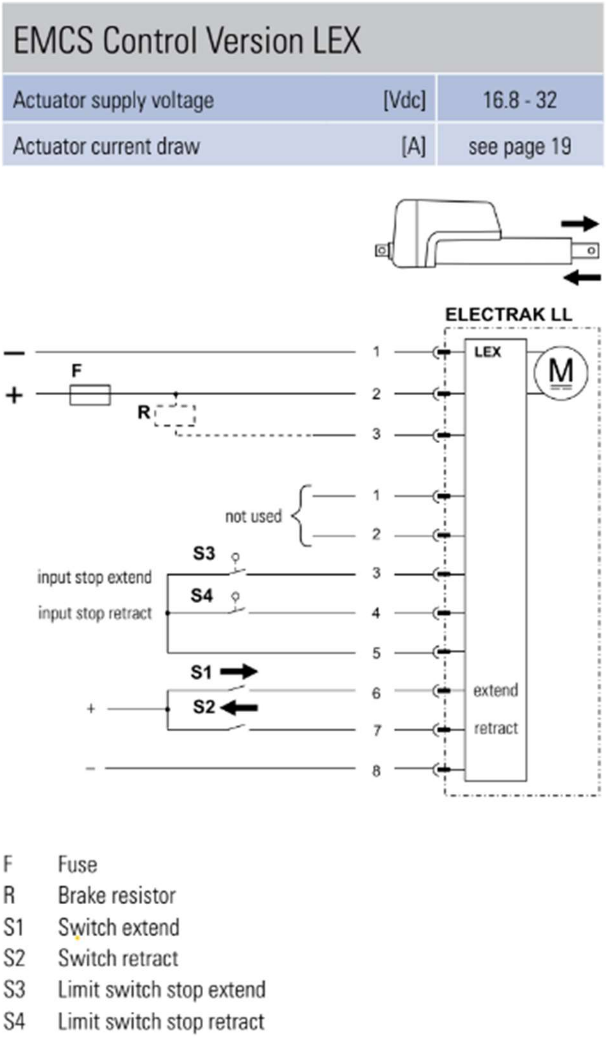


Figure 16. Hardware setup for knee joint control.



EMCS Control Version LEX		
Actuator supply voltage	[Vdc]	16.8 - 32
Actuator current draw	[A]	see page 19

F	Fuse
R	Brake resistor
S1	Switch extend
S2	Switch retract
S3	Limit switch stop extend
S4	Limit switch stop retract

Figure 17. Wiring diagram for linear actuator.

As for the control code, the Arduino IDE was used to create an actuator control class and main C++ file which calls the methods of the class using a serial Bluetooth connection over a cell phone for ease of use during expo or, if Bluetooth is not desired as in the case of the complete control scheme for the exoskeleton, it is able to be called in other main files to determine angular location, activate soft-stops at angles 93 and 173 degrees, and work as a basic P-Controller. This code is included in Appendix F, which currently has the setup for Bluetooth.

3.5 Lessons Learned

Several lessons were learned while manufacturing and assembling the knee joint. Under-sizing the holes on the links that were cut by the water jet was found to be very important, as the position tolerancing of the holes was poor. Additionally, the profile tolerancing of the water jet is also not optimal and a fair amount of grinding was necessary to improve the profile of the links.

We also learned that with high infill, 3D-printed fixtures work well for securing parts on the mill. There was some initial concern about the strength of PLA and that the printed part may melt. The fixtures held together well and did not get too hot when sufficient coolant was used. Overall, the 3D-printed fixtures worked very well for drilling and reaming the holes for bearings and bolts.

The manufacturing and assembly of the prototype took longer than expected. We originally planned to complete manufacturing by the linear actuator's arrival, but manufacturing ended up being completed a few days later. This was due to extended manufacturing time and lack of machine availability, though the delay was not extremely detrimental because we anticipated the delays.

4 Design Verification

After finishing the prototype, we carried out various tests to determine whether the system meets each specification outlined in Table 1. Each specification represents a key aspect of our design that our sponsor wanted us to include.

4.1 Specifications

The Design Verification Plan, found in Appendix D, outlines which tests were performed for each specification, what the acceptance criteria was, what equipment and parts we used, who was responsible for the test, and when the tests were completed.

Since CDR, some changes have been made to the test procedures. We decided not to perform a waterproof test because the prototype will solely be used indoors. We also determined that the life of components test is not feasible for this year's timeline but is recommended if the biomechanical knee joint is used in the final prototype.

Table 1. Updated design specification sheet.

Spec #	Specification Description	Requirement or Target (units)	Plan to Show
1	Weight	<15 lbf	Inspection
2	Integration with Exoskeleton	Integrates with soft goods and linkages senior project teams	Both senior project teams will complete manufacturing on a similar timeline; will test knee with their components.
3	Load Carrying Capability	Does not fail due to dynamic loads at <1.5 mph	Attach joint to a frame, run the joint and apply an impact to the joint at a speed of less than 1.5 mph
4	Control of Range of Motion	Able to stop even if power is cut at any point in actuation and full extension (180 degrees) and flexion (90 degrees) possible	Cut off connection to battery and determine if joint stops, and move device manually, using a potentiometer to determine full extension and flexion angles.
5	Cost	Maximum $2,000	Inspection
6	Manufacturable	Inspection	Inspection
7	Wearability	There is 2 inches of clearance between the point of the hip and the center of linkage rotation	Strap the knee to a person of similar dimensions to the intended user and measure the distance from the end of the actuator to the point of the hip.
8	Loudness	Less than 70 dB	Will capture and analyze the sound emitted by the joint

Most of the tests we completed have a pass/fail criteria, so measurements are not necessary for many of the tests when determining whether they pass or fail. For our other tests, we measured and recorded the respective values and compared them to the rating required to pass. These tests include weight, comparability to knee size, and noise level/loudness, and their pass conditions were developed based on the required values for successful or safe operation. The knee joint must weigh less than 15 lbf to be supported easily by the exoskeleton, the stroke length must fit onto the user's due to size constraints and be under 70 dB while running to avoid damaging the user's hearing. We have detailed test procedures for each specification that requires testing and included them in Appendix E. Each of these procedures outlines the required materials for the test and documents the detailed steps for completing the test.

4.2 Testing and Results

The control of range of motion test involved extending and retracting the actuator through various positions and comparing the angular potentiometer output readings to physical values measured with a protractor. The important positions were the fully retracted and fully extended positions: 93 and 175 degrees, respectively. In between these positions, 3 measurements were done at approximately a quarter, half, and three-quarters distance between fully retracted and fully extended. For each position, three potentiometer and protractor measurements were taken, with their average values being compared to determine percent error and uncertainty analysis. The uncertainty analysis and data are attached in Appendix G.

During this test, data on the speed of the actuator during retraction and extension was collected using the time signature of each potentiometer reading between full extension and retraction in Arduino IDE. It was also confirmed that the actuator will stop at its current position when power is cut. The control of range of motion test setup is shown in Figure 18.

Figure 18. Angular position and velocity test setup. Readings from potentiometer on computer (in background) were compared to physical readings from a protractor.

We completed the load carrying capability test in the TECHE lab using a frame created by LLEAP to support the knee joint for testing. We created weights for the test using a bucket filled with various pieces of aluminum as weight, and a hanging scale attached to the knee joint and bucket using a C-clamp. We attached the knee joint to the frame at the tibia connection and the weight was applied where the hip joint will be connected. In this test, the knee joint began in the fully retracted position and was then loaded with weights of 25, 50, 75, and 100 lbf. The joint was then extended through its full range of motion, with the voltage input set to the nominal value of 24V, mimicking the sit to stand motion. The joint would pass if it was able to carry the weighted bucket to the maximum angle without any indications of struggle, likely in the form of a motor stall (i.e., increase in noise, temperature, vibration, etc.). This test was done concurrently with the noise level test, so any signs of stalling or other struggle could be easily – and quantitatively – determined. At the end of this test, it was found that the joint fully passed; it was able to carry all loads and showed no signs of potential failure. The load carrying capacity test setup is shown in Figure 19.

Figure 19. Experimental apparatus/setup for load capacity and noise tests.

As mentioned above, we carried out the loudness test and the time as the load carrying capability test concurrently. This was done for two reasons: to provide a way to determine if the joint struggled during loading and to determine whether the actuator is louder under loaded or no-load conditions. We began this test by measuring the ambient sound level of the room using the iOS app Decibel X. Because a meeting was beginning, the noise level was higher than expected, with ambient noise found to be approximately 75 dB. We then held the phone – with the app recording – about a foot away from the knee joint and began the load carrying capability test. As can be seen in the results in Appendix E, the maximum decibel rating was 77 dB, and occurred when the joint had no load applied to it. The values measured during loading were all around 75 dB. Because the ambient noise was measured to be 75 dB, these values may be slightly higher or lower. While the knee joint does fail the loudness test (as it exceeds the failure criteria of 70 dB), it is less than the 85 dB rating that necessitates ear protection for exposure over 6 hours. Our initial goal for loudness was 70 dB because sounds below that level are allowed for an indefinite time period without hearing damage, but it is more realistic that the exoskeleton will only be used for 6 hours or less at a time which means any sound below 85 dB should not damage the user's ears.

To carry out the integration with exoskeleton test, we bolted the hip joint and femur structure to the knee. Because the 2023 cycloidal hip joint took more time than expected to manufacture, the 2022 planetary design was used to demonstrate exoskeleton integration. The bolted connection to the hip was very difficult to attach to the knee's femur connection due to the bolts available. For future integration, socket head screws will be used to make the attachment easier. The fully assembled single-leg exoskeleton prototype is shown in Figure 20.

Figure 20. Knee joint integration with hip joint and tibia structure.

5 Discussion & Recommendations

After completing our project and testing the knee joint with the rest of the exoskeleton, we have come up with recommendations for future improvements. This section includes a discussion of our finished prototype and suggestions for design refinement.

5.1 What we learned

Several learning outcomes were discovered throughout this design process. We learned that it is not feasible to find an off-the-shelf linear actuator that meets all exoskeleton requirements. When conducting market research on available off-the-shelf actuators, the Thomson linear actuator met the most specifications, but failed to be small enough and did not have speed control. To move forward with this design, a custom actuator must either be made by LLEAP or outsourced to another company. In addition, we became aware of the importance of accounting for lead times. Due to our actuator arriving late in the quarter, manufacturing was delayed, which also pushed back the testing phase of our project. More time to test would have allowed design requirements to be further evaluated.

We gained an understanding of how to make design changes during manufacturing, as alterations had to be made during design and production. Finding solutions that were feasible while meeting all design requirements was challenging.

We learned that with wearable devices, power density is critical. Although the actuator's location on the thigh helps distribute weight of the suit and decrease mass moment of inertia, if the actuator is too large it cannot be worn by users with a wide height range. With the cycloidal hip design, the purchased actuator would be able to fit onto the thigh of our challenger, but due to the manufacturing time of the cycloidal drive, LLEAP temporarily used an older planetary hip design for the 2023 suit. This planetary drive was too large for our intended user, which demonstrates how changes to adjacent designs largely influence the feasibility of our design.

We learned that communication is crucial, especially between the adjacent mechanical teams (the hip and the linkage teams). Although communication was improved throughout the project, keeping other teams constantly up to date on our design is difficult and we could have done a better job.

5.2 Recommendations and Next Steps

If our group was to continue with this design, we would develop a custom linear actuator to make this design more wearable and accessible to a variety of users. The actuator should have built-in speed control, minimized weight, and higher power density. The power density must result in a size reduction substantial enough to allow the knee joint to fit on the thigh of a 5-foot 2-inch user. This range of acceptable heights is necessary to allow for the design to be adapted more easily for future users of smaller stature and to allow the exoskeleton to be tested by a challenger who has experience with exoskeletons prior to our intended user. Our team would also get access to biomechanical imaging techniques that would help determine exact link lengths and the amount of change in the knee's center of rotation. As it is difficult to acquire magnetic resonance imaging (MRI) for several users, finding a way to externally find the amount of change in the center of knee rotation would be optimal. This may be achievable using marker tracking to perform motion analysis.

If we were to do this project again, we would focus more on biomechanics at the start of the project. We would also purchase a linear actuator earlier on, as shipping time delayed our progress. When purchasing the actuator, instead of emailing one engineer directly, it may be more effective to speak to several engineers at the company, as well as communicate with several control team members. This includes personnel who work on mechatronics, software, and sensing to ensure that the actuator will be compatible with all controls applications required by the system.

5.3 Recommendations for use

Although design changes need to be made, this prototype can be used for control and wearability testing. The user manual, shown in Appendix A, should be used to ensure the prototype is safely and effectively used. Having a physical knee joint model allows mechatronics to begin testing multiple joints together, and eventually simulate gait motion. This prototype will help achieve integration of the mechanical and control systems.

The completed knee joint should be used for wearability testing, as this is the first wearable knee joint LLEAP has achieved. The knee joint can be used to conduct tests such as the ability for a paralyzed user to transfer into the suit, misalignment, comfortability, and soft goods placement.

6 Conclusion

This project created a biomechanically accurate knee joint for the Lower Limb Exoskeleton Assist Project using a four-bar linkage and linear actuator. This project was successful in force, integration, and manufacturability, but did not achieve wearability and controls requirements. For this design to be developed further, a custom or improved linear actuator must be integrated that meets all control, weight, and size requirements. This will make the device more accessible to a variety of users and improve device wearability. The design’s biomechanical accuracy was difficult to quantify, as it was not possible to determine correct link lengths based on the user's geometry as well as the amount of change in the knee’s center of rotation. However, with proper imaging techniques and updated link lengths based on a defined center of rotation path for the user’s knee, the correct biomechanical motion can likely be achieved in the future.

This project discovered the advantages and limitations of a four-bar linkage and linear actuator approach to creating a biomechanical knee joint. The findings of this project will allow for the development of a future design that better meets the requirements of an exoskeleton knee joint, enabling a paralyzed individual to walk again.

7 References

[1] Bessler-Etten, Jule, et al. "Assessing Effects of Exoskeleton Misalignment on Knee Joint Load= during Swing Using an Instrumented Leg Simulator - Journal of Neuroengineering and Rehabilitation." *BioMed Central*, 29 Jan. 2022, jneuroengrehab.biomedcentral.com/articles/10.1186/s12984-022-00990-z.

[2] Billings, John Scott. *Steady Ratio Four-Bar Linkage for Genuflective Energy Harvesting*. Patent EP3362002B1. 4 Dec. 2019.

Appendices

Appendix A – User Manual

This user's manual includes instructions for how to actuate this knee joint. Read this section entirely including all safety warnings and cautions before using the product.

Mechanical Safety

The operation of the knee joint carries with it inherent risks. These risks include pinch points, environmental hazards (such as a tripping hazard if on ground), or failures in the design and control system that could cause harm to the user and those around. While these risks are significant, they can be successfully eliminated through the following steps:

The user should:

- Wear long pants
- Wear closed toed shoes

The operator should:

- Have long hair tied back
- Wear safety glasses during testing
- Wear closed toed shoes

Make sure to keep hands and clothing away from the knee joint and pinch points whenever the actuator is connected to power. Pinch points are as follows:

1. The center of the four-bar linkage. DO NOT put hands near this during operation (Figure 21).

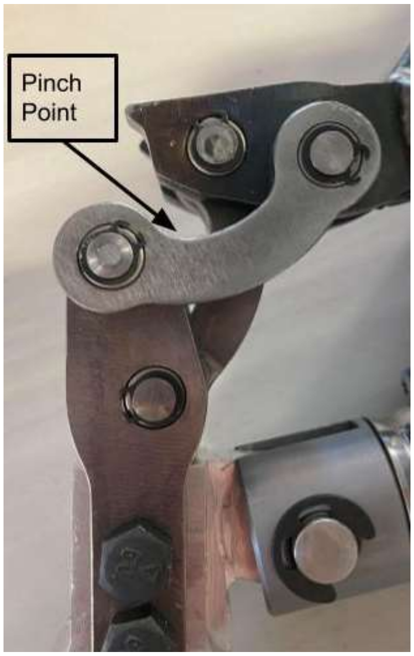


Figure 21. Pinch points on the four-bar linkage.

2. DO NOT grab the angled stock during operation. When going into full extension, there will not be space between the stock and the actuator.

Maintenance Guidelines

1. Grease needle roller bearings monthly
2. Check all welds monthly for cracks or signs of failure
3. Detailed list of parts for ordering replacements is included in Appendix C

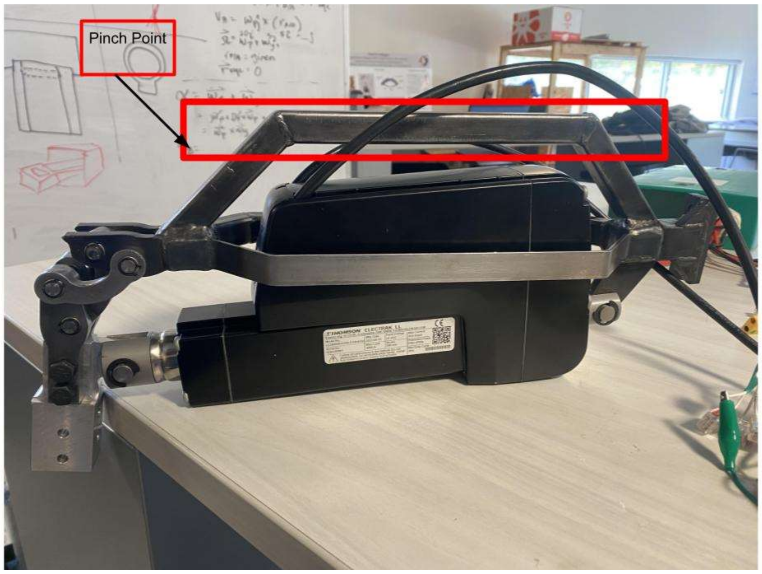


Figure 22. Pinch point between the linear actuator and frame.

Electrical Safety

Do not work on electrical when the battery is connected to the actuator.

- Ensure no bodily objects or clothing are in/near pinch points.
- Visually check hard stops and ensure none are deformed in any manner.
- Ensure the surrounding area is clear of all hazards (i.e., objects lying on ground, spills, etc.)
- Follow the below “Controlling the Joint” procedure to ensure proper electrical connections and methodology.
- If at any point the joint is planned to be placed on the user, run the joint and ensure all hard stops work as intended, as well as the code.

1. Do not wrap your hand around cables.
2. Make sure electronics connected to actuator are fully connected before battery is connected.

Wiring

There are 11 wires that come from the linear actuator, and they are grouped in 2 sets: 1 set of 3 (labeled 1-3) and 1 set of 8 (labeled 1-8).

Positive power from the switching regulator should be connected to line 2 (of the set of 3) and to line 3 (of the same set) through a set of brake resistors. Ground, also from the switching regulator, should be connected to line 1 of the same set. To ensure proper safety, a breaker/fuse should also be connected to line 2 between the regulator and actuator.

For the second set of wires, 1 – 5 are not used/connected to anything (1 and 2 are unnecessary and 3-5 are used for limit switches which are also not used). Lines 6 and 7 are connected to the transducers and correlate to the extend and retract lines, respectively. Line 8 is connected to the switching regulators ground.

See Figure 23 for the wiring diagram of the linear actuator.

Controlling the Actuator

The control system for the knee joint utilizes an ESP32 MCU board to switch the direction of the linear actuator and whether it is off or on. This is done through transistors - acting as switches - on lines 6 and 7 of the linear actuator which are controlled through two GPIO pins on the MCU board. The system also incorporates an error feedback mechanism - done with an angular potentiometer at the joint - as a reference for the internal code used to control the system. For this expo, the code is set up so that an angle is input which in turn activates the actuator until the angular potentiometer reports it has been reached. The specific steps for control are as follows:

- Ensure the break resistors are connected to power line 3 as shown below.
- Ensure the breaker is connected in series with power line 2.
- Ensure pins 14 (extend) and 12 (retract) of the ESP32 MCU are connected to the BJTs through a series resistor.
- Once all connections have been checked and confirmed as proper, connect the switching regulator to the battery (while ensuring the ESP32 code is keeping the transistors in ‘disconnect’ mode).
- Input into the ESP32 the desired angle for the joint.

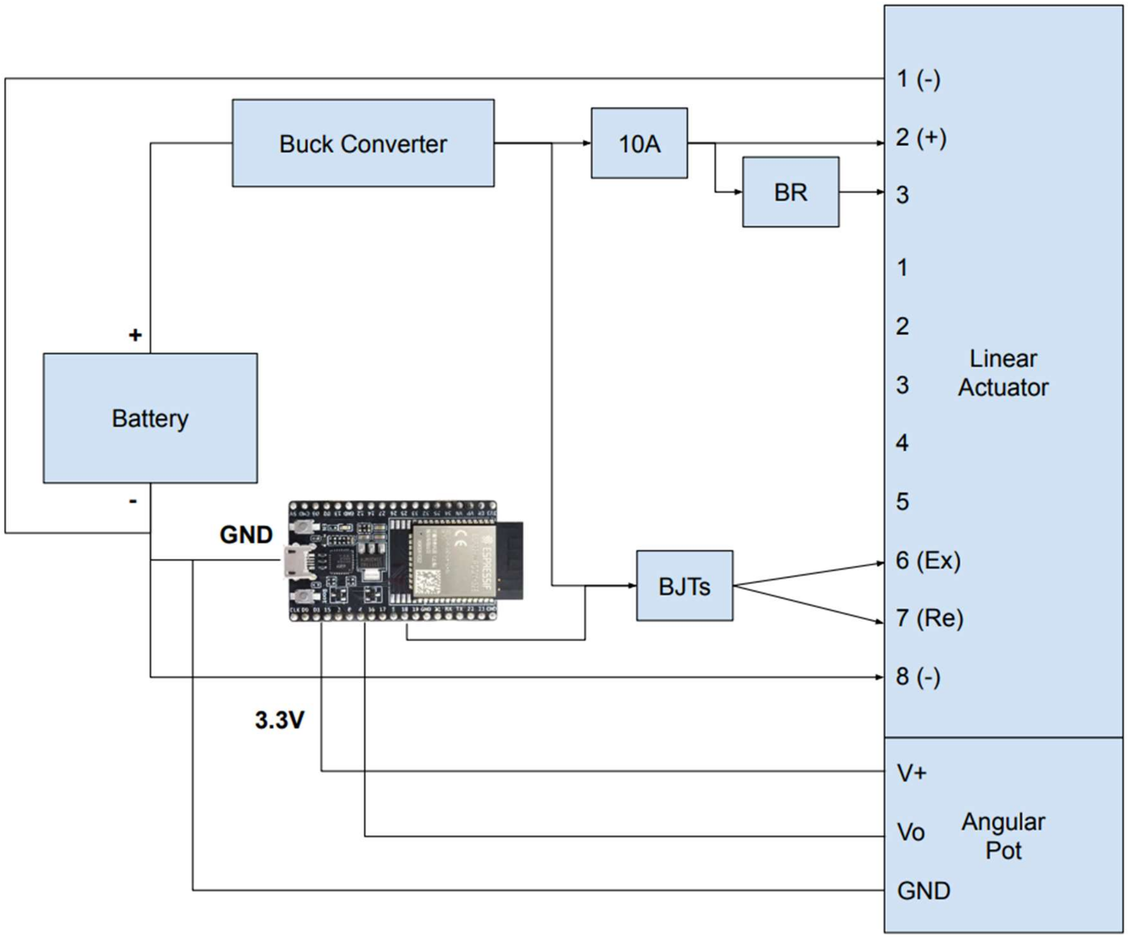
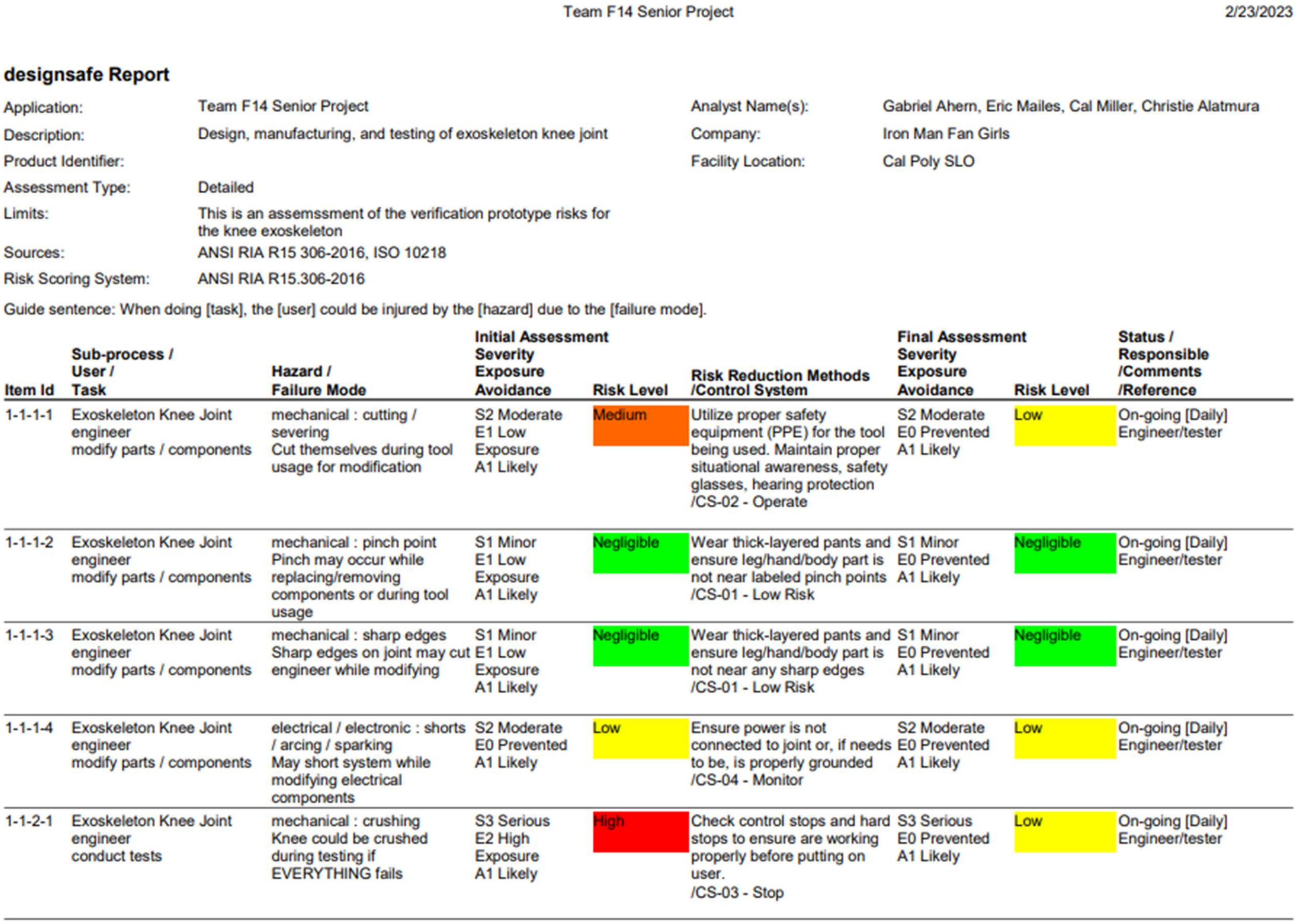


Figure 23. Linear actuator electrical diagram.

- Do not apply PWM to the actuator.
- Do not apply a current larger than 10.5A to the actuator.
- Do not apply a voltage smaller than 16V or larger than 32V.
- Do not grab the handles.
- Do not pull and push on actuator.

Appendix B – Risk Assessment



Team F14 Senior Project 2/23/2023

designsafe Report

Application:	Team F14 Senior Project	Analyst Name(s):	Gabriel Ahern, Eric Mailes, Cal Miller, Christie Alatmura
Description:	Design, manufacturing, and testing of exoskeleton knee joint	Company:	Iron Man Fan Girls
Product Identifier:		Facility Location:	Cal Poly SLO
Assessment Type:	Detailed		
Limits:	This is an assemssment of the verification prototype risks for the knee exoskeleton		
Sources:	ANSI RIA R15 306-2016, ISO 10218		
Risk Scoring System:	ANSI RIA R15.306-2016		

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

Item Id	Sub-process / User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Avoidance	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Exposure Avoidance	Risk Level	Status / Responsible /Comments /Reference
1-1-1-1	Exoskeleton Knee Joint engineer modify parts / components	mechanical : cutting / severing Cut themselves during tool usage for modification	S2 Moderate E1 Low Exposure A1 Likely	Medium	Utilize proper safety equipment (PPE) for the tool being used. Maintain proper situational awareness, safety glasses, hearing protection /CS-02 - Operate	S2 Moderate E0 Prevented A1 Likely	Low	On-going [Daily] Engineer/tester
1-1-1-2	Exoskeleton Knee Joint engineer modify parts / components	mechanical : pinch point Pinch may occur while replacing/removing components or during tool usage	S1 Minor E1 Low Exposure A1 Likely	Negligible	Wear thick-layered pants and ensure leg/hand/body part is not near labeled pinch points /CS-01 - Low Risk	S1 Minor E0 Prevented A1 Likely	Negligible	On-going [Daily] Engineer/tester
1-1-1-3	Exoskeleton Knee Joint engineer modify parts / components	mechanical : sharp edges Sharp edges on joint may cut engineer while modifying	S1 Minor E1 Low Exposure A1 Likely	Negligible	Wear thick-layered pants and ensure leg/hand/body part is not near any sharp edges /CS-01 - Low Risk	S1 Minor E0 Prevented A1 Likely	Negligible	On-going [Daily] Engineer/tester
1-1-1-4	Exoskeleton Knee Joint engineer modify parts / components	electrical / electronic : shorts / arcing / sparking May short system while modifying electrical components	S2 Moderate E0 Prevented A1 Likely	Low	Ensure power is not connected to joint or, if needs to be, is properly grounded /CS-04 - Monitor	S2 Moderate E0 Prevented A1 Likely	Low	On-going [Daily] Engineer/tester
1-1-2-1	Exoskeleton Knee Joint engineer conduct tests	mechanical : crushing Knee could be crushed during testing if EVERYTHING fails	S3 Serious E2 High Exposure A1 Likely	High	Check control stops and hard stops to ensure are working properly before putting on user. /CS-03 - Stop	S3 Serious E0 Prevented A1 Likely	Low	On-going [Daily] Engineer/tester

Item Id	Sub-process / User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Avoidance	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Exposure Avoidance	Risk Level	Status / Responsible /Comments /Reference
1-1-2-2	Exoskeleton Knee Joint engineer conduct tests	mechanical : pinch point May be pinched by connection from knee joint to tester	S1 Minor E2 High Exposure A1 Likely	Low	Wear thick-layered pants and ensure leg/hand/body part is not being pinched while connecting joint to tester /CS-02 - Operate	S1 Minor E0 Prevented A1 Likely	Negligible	On-going [Daily] Engineer/tester
1-1-2-3	Exoskeleton Knee Joint engineer conduct tests	mechanical : unexpected start If knee joint unexpectedly starts before testers leg is fully secure	S2 Moderate E1 Low Exposure A1 Likely	Medium	Ensure power is disconnected until joint is fully attached to tester (after prior testing of control/hard stops) /CS-04 - Monitor	S2 Moderate E0 Prevented A1 Likely	Low	On-going [Daily] Engineer/tester
1-1-2-4	Exoskeleton Knee Joint engineer conduct tests	slips / trips / falls : slip May slip while testing knee joint exo movement	S2 Moderate E1 Low Exposure A2 Not Likely	Medium	Ensure support systems (crutches, rails, etc.) are nearby during testing. /CS-04 - Monitor	S2 Moderate E0 Prevented A1 Likely	Low	TBD Engineer/tester
1-1-2-5	Exoskeleton Knee Joint engineer conduct tests	slips / trips / falls : trip May trip while testing knee joint exo movement	S2 Moderate E1 Low Exposure A2 Not Likely	Medium	Ensure support systems (crutches, rails, etc.) are nearby during testing. /CS-04 - Monitor	S2 Moderate E0 Prevented A1 Likely	Low	TBD Engineer/tester
1-1-2-6	Exoskeleton Knee Joint engineer conduct tests	slips / trips / falls : fall hazard from elevated work May fall while testing knee joint exo movement	S2 Moderate E1 Low Exposure A1 Likely	Medium	Ensure support systems (crutches, rails, etc.) are nearby during testing. /CS-04 - Monitor	S2 Moderate E0 Prevented A2 Not Likely	Low	TBD Engineer/tester
1-1-2-7	Exoskeleton Knee Joint engineer conduct tests	ergonomics / human factors : excessive force / exertion Knee joint actuation faster than tester knee can handle/is expecting	S3 Serious E2 High Exposure A2 Not Likely	High	Check speed/torque outputs before putting on tester and ensure are within correct range. Have means of disconnecting power quickly during testing as well /CS-03 - Stop	S3 Serious E0 Prevented A1 Likely	Low	On-going [Daily] Engineer/tester
1-1-2-8	Exoskeleton Knee Joint engineer conduct tests	ergonomics / human factors : lifting / bending / twisting Knee joint out of alignment with testers knee	S2 Moderate E2 High Exposure A1 Likely	Medium	Check alignment of joint before putting on tester and confirm is correct. /CS-04 - Monitor	S2 Moderate E0 Prevented A1 Likely	Low	On-going [Daily] Engineer/tester

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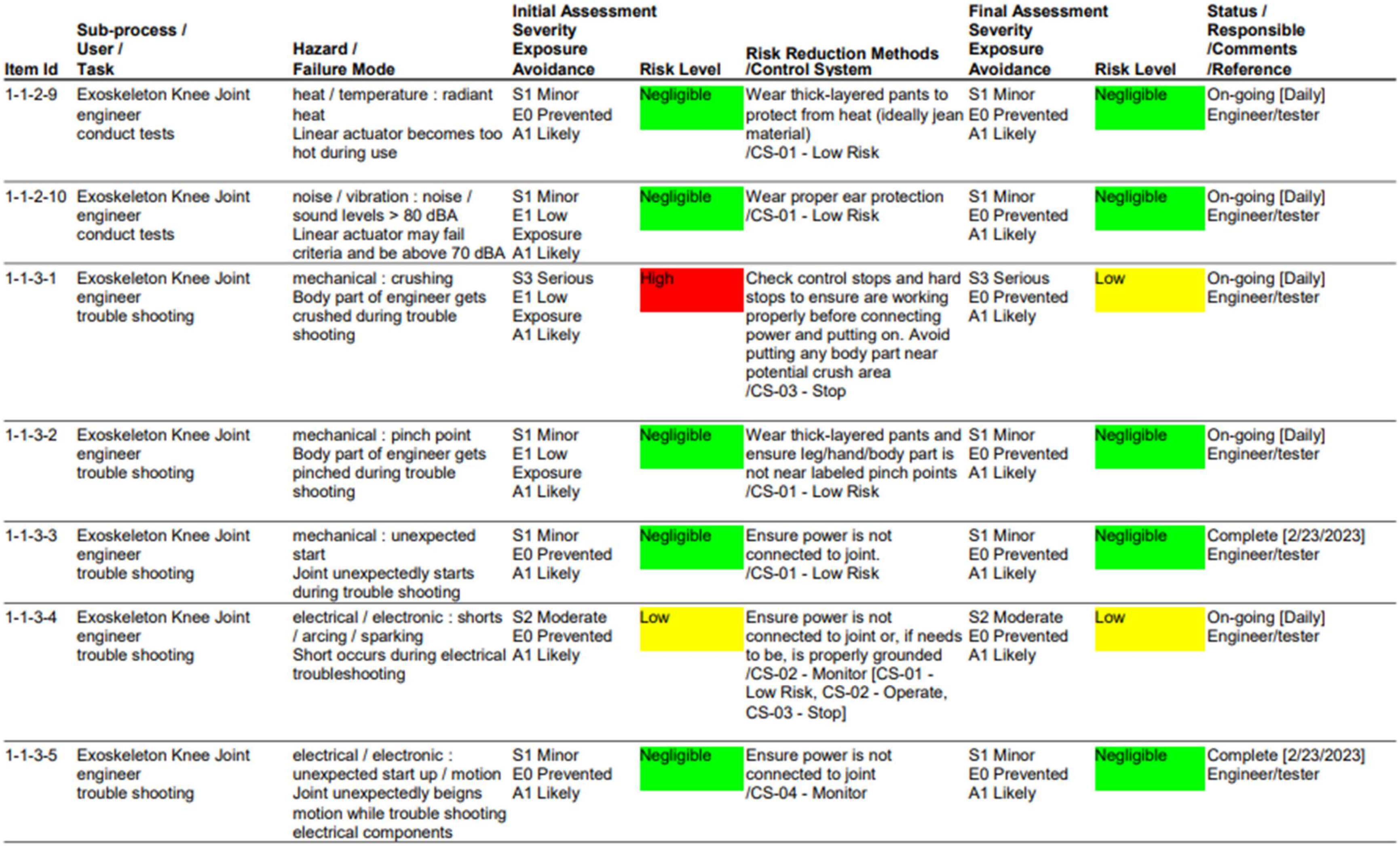
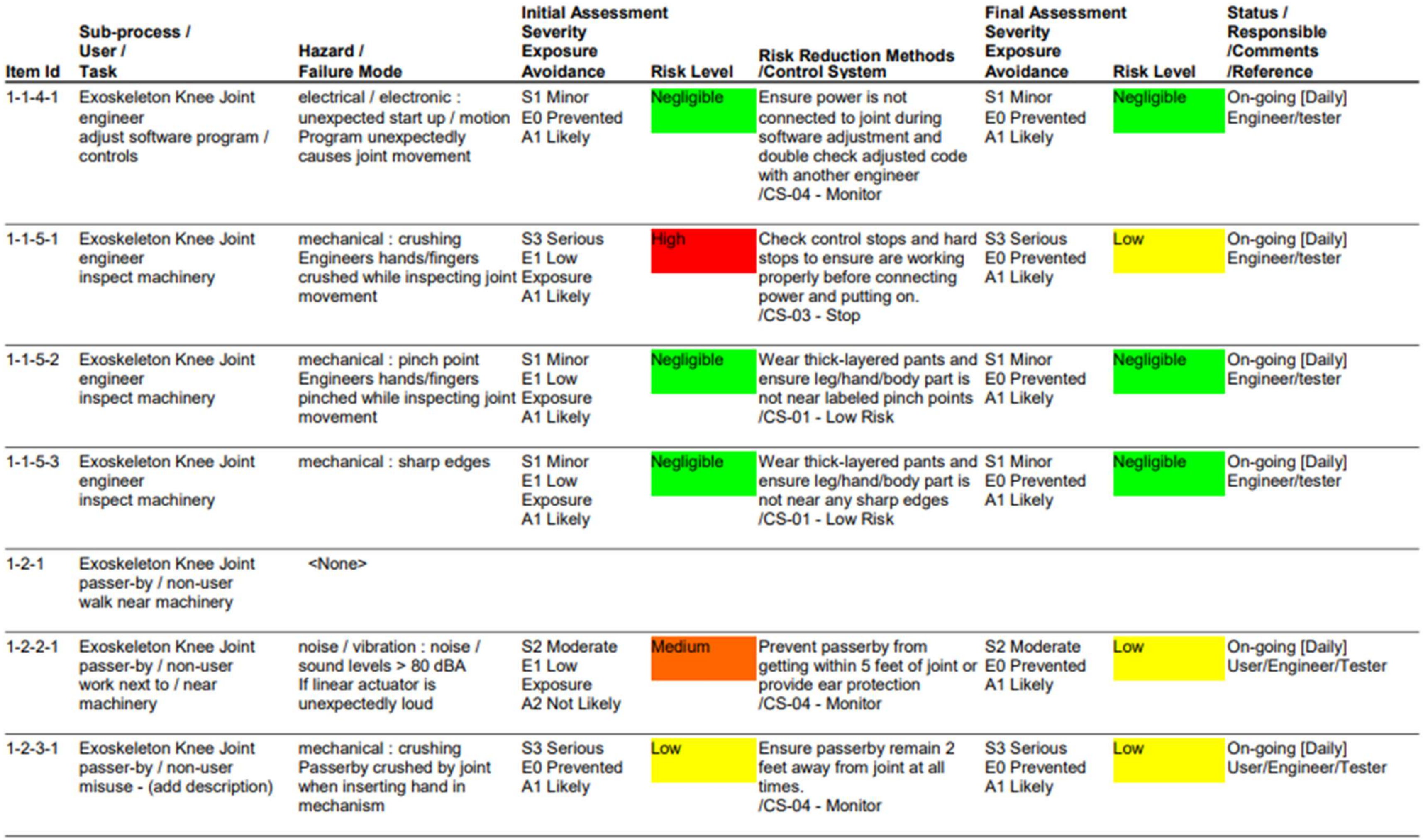
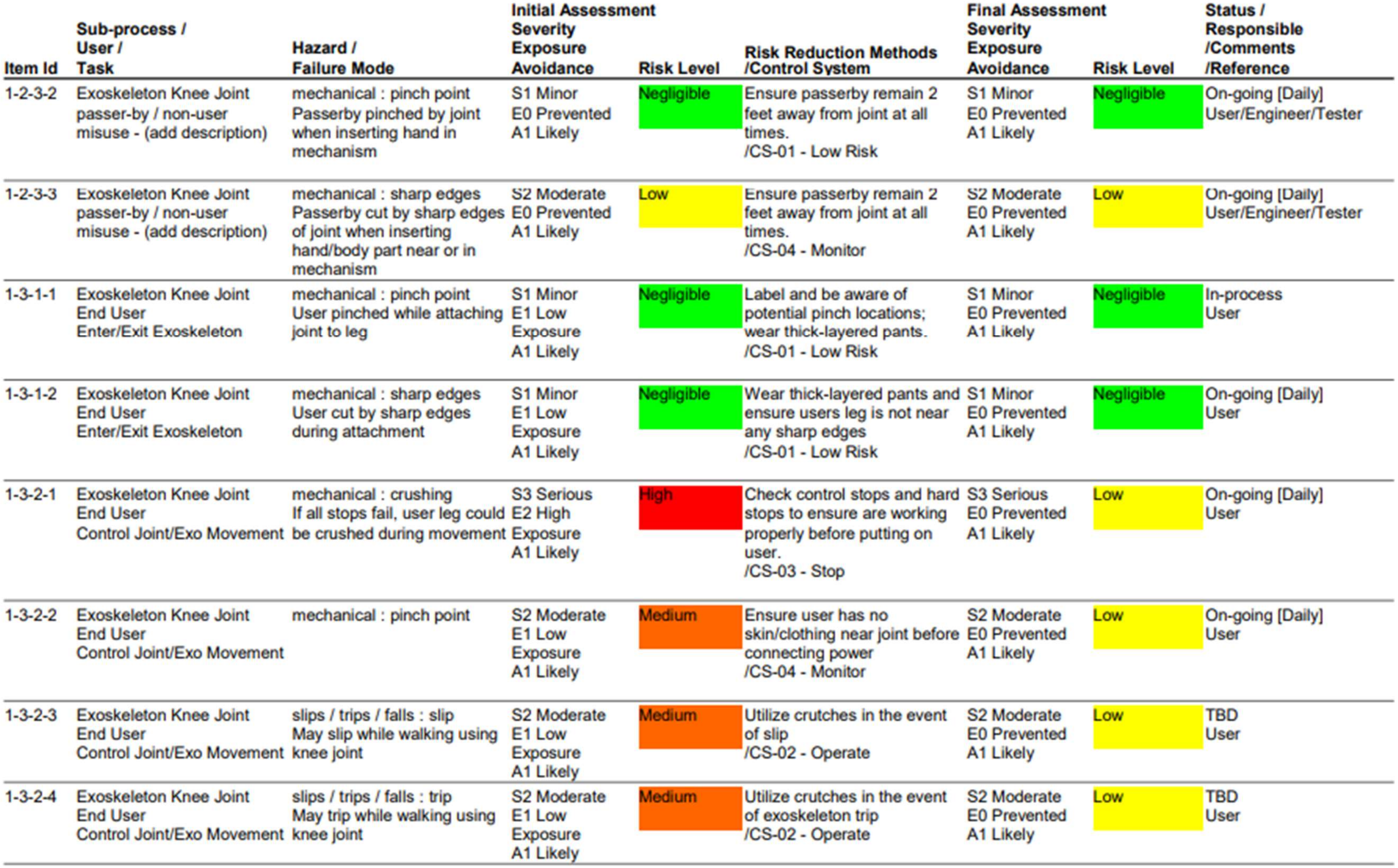
Privileged and Confidential Information



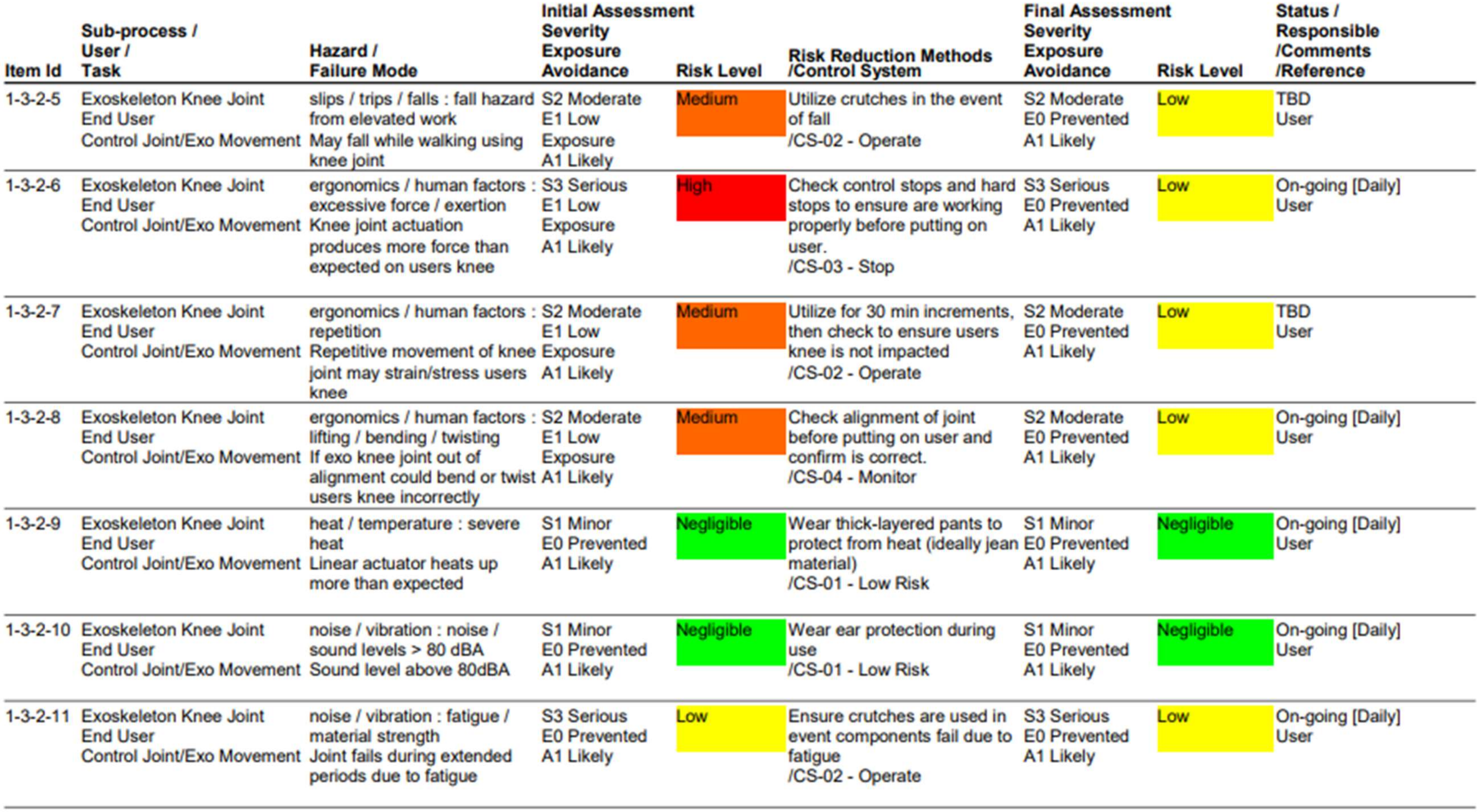
Item Id	Sub-process / User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Avoidance	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Exposure Avoidance	Risk Level	Status / Responsible /Comments /Reference
1-1-2-9	Exoskeleton Knee Joint engineer conduct tests	heat / temperature : radiant heat Linear actuator becomes too hot during use	S1 Minor E0 Prevented A1 Likely	Negligible	Wear thick-layered pants to protect from heat (ideally jean material) /CS-01 - Low Risk	S1 Minor E0 Prevented A1 Likely	Negligible	On-going [Daily] Engineer/tester
1-1-2-10	Exoskeleton Knee Joint engineer conduct tests	noise / vibration : noise / sound levels > 80 dBA Linear actuator may fail criteria and be above 70 dBA	S1 Minor E1 Low Exposure A1 Likely	Negligible	Wear proper ear protection /CS-01 - Low Risk	S1 Minor E0 Prevented A1 Likely	Negligible	On-going [Daily] Engineer/tester
1-1-3-1	Exoskeleton Knee Joint engineer trouble shooting	mechanical : crushing Body part of engineer gets crushed during trouble shooting	S3 Serious E1 Low Exposure A1 Likely	High	Check control stops and hard stops to ensure are working properly before connecting power and putting on. Avoid putting any body part near potential crush area /CS-03 - Stop	S3 Serious E0 Prevented A1 Likely	Low	On-going [Daily] Engineer/tester
1-1-3-2	Exoskeleton Knee Joint engineer trouble shooting	mechanical : pinch point Body part of engineer gets pinched during trouble shooting	S1 Minor E1 Low Exposure A1 Likely	Negligible	Wear thick-layered pants and ensure leg/hand/body part is not near labeled pinch points /CS-01 - Low Risk	S1 Minor E0 Prevented A1 Likely	Negligible	On-going [Daily] Engineer/tester
1-1-3-3	Exoskeleton Knee Joint engineer trouble shooting	mechanical : unexpected start Joint unexpectedly starts during trouble shooting	S1 Minor E0 Prevented A1 Likely	Negligible	Ensure power is not connected to joint. /CS-01 - Low Risk	S1 Minor E0 Prevented A1 Likely	Negligible	Complete [2/23/2023] Engineer/tester
1-1-3-4	Exoskeleton Knee Joint engineer trouble shooting	electrical / electronic : shorts / arcing / sparking Short occurs during electrical troubleshooting	S2 Moderate E0 Prevented A1 Likely	Low	Ensure power is not connected to joint or, if needs to be, is properly grounded /CS-02 - Monitor [CS-01 - Low Risk, CS-02 - Operate, CS-03 - Stop]	S2 Moderate E0 Prevented A1 Likely	Low	On-going [Daily] Engineer/tester
1-1-3-5	Exoskeleton Knee Joint engineer trouble shooting	electrical / electronic : unexpected start up / motion Joint unexpectedly beigns motion while trouble shooting electrical components	S1 Minor E0 Prevented A1 Likely	Negligible	Ensure power is not connected to joint /CS-04 - Monitor	S1 Minor E0 Prevented A1 Likely	Negligible	Complete [2/23/2023] Engineer/tester



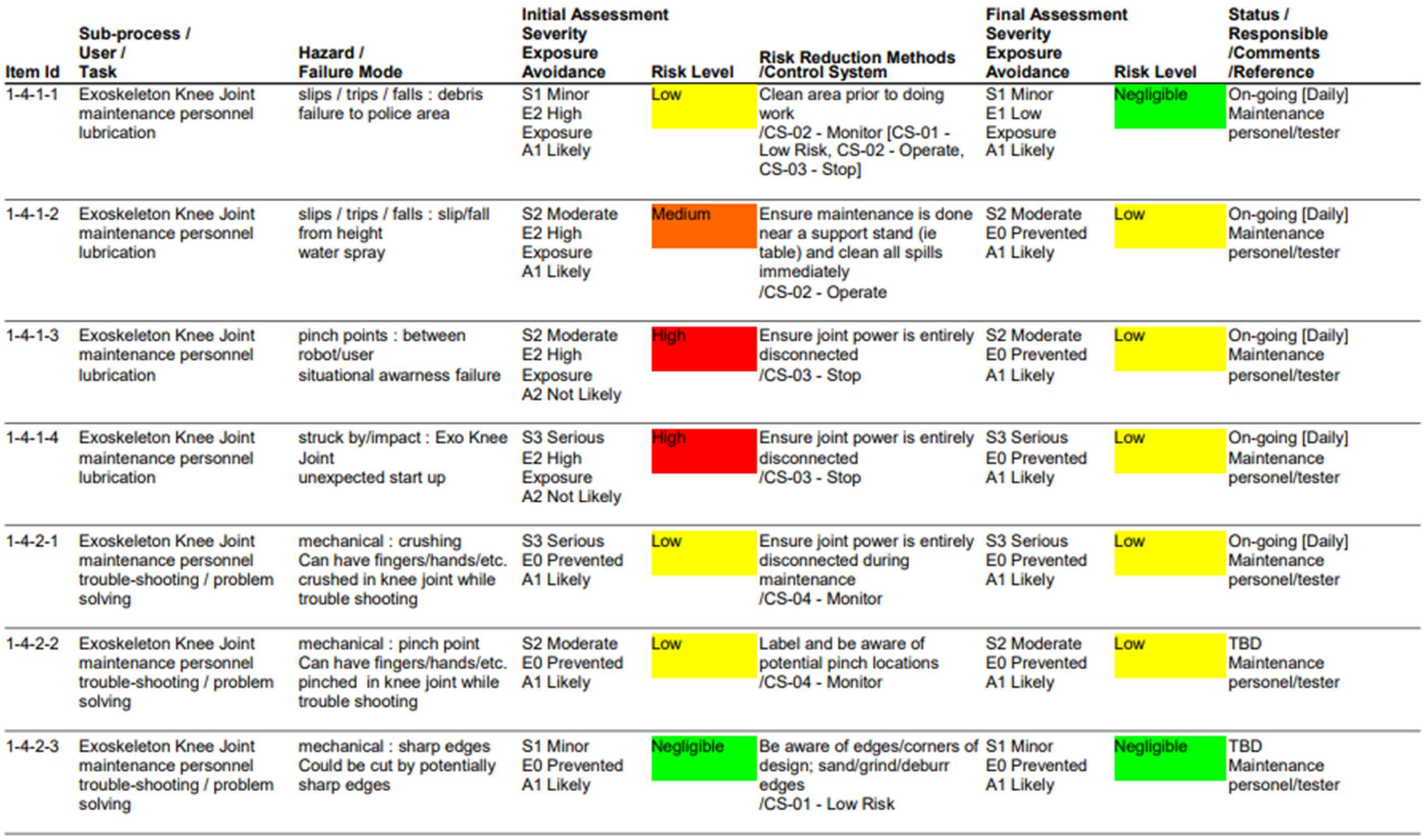
Item Id	Sub-process / User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Avoidance	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Exposure Avoidance	Risk Level	Status / Responsible /Comments /Reference
1-1-4-1	Exoskeleton Knee Joint engineer adjust software program / controls	electrical / electronic : unexpected start up / motion Program unexpectedly causes joint movement	S1 Minor E0 Prevented A1 Likely	Negligible	Ensure power is not connected to joint during software adjustment and double check adjusted code with another engineer /CS-04 - Monitor	S1 Minor E0 Prevented A1 Likely	Negligible	On-going [Daily] Engineer/tester
1-1-5-1	Exoskeleton Knee Joint engineer inspect machinery	mechanical : crushing Engineers hands/fingers crushed while inspecting joint movement	S3 Serious E1 Low Exposure A1 Likely	High	Check control stops and hard stops to ensure are working properly before connecting power and putting on. /CS-03 - Stop	S3 Serious E0 Prevented A1 Likely	Low	On-going [Daily] Engineer/tester
1-1-5-2	Exoskeleton Knee Joint engineer inspect machinery	mechanical : pinch point Engineers hands/fingers pinched while inspecting joint movement	S1 Minor E1 Low Exposure A1 Likely	Negligible	Wear thick-layered pants and ensure leg/hand/body part is not near labeled pinch points /CS-01 - Low Risk	S1 Minor E0 Prevented A1 Likely	Negligible	On-going [Daily] Engineer/tester
1-1-5-3	Exoskeleton Knee Joint engineer inspect machinery	mechanical : sharp edges	S1 Minor E1 Low Exposure A1 Likely	Negligible	Wear thick-layered pants and ensure leg/hand/body part is not near any sharp edges /CS-01 - Low Risk	S1 Minor E0 Prevented A1 Likely	Negligible	On-going [Daily] Engineer/tester
1-2-1	Exoskeleton Knee Joint passer-by / non-user walk near machinery	<None>						
1-2-2-1	Exoskeleton Knee Joint passer-by / non-user work next to / near machinery	noise / vibration : noise / sound levels > 80 dBA If linear actuator is unexpectedly loud	S2 Moderate E1 Low Exposure A2 Not Likely	Medium	Prevent passerby from getting within 5 feet of joint or provide ear protection /CS-04 - Monitor	S2 Moderate E0 Prevented A1 Likely	Low	On-going [Daily] User/Engineer/Tester
1-2-3-1	Exoskeleton Knee Joint passer-by / non-user misuse - (add description)	mechanical : crushing Passerby crushed by joint when inserting hand in mechanism	S3 Serious E0 Prevented A1 Likely	Low	Ensure passerby remain 2 feet away from joint at all times. /CS-04 - Monitor	S3 Serious E0 Prevented A1 Likely	Low	On-going [Daily] User/Engineer/Tester



Item Id	Sub-process / User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Avoidance	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Exposure Avoidance	Risk Level	Status / Responsible /Comments /Reference
1-2-3-2	Exoskeleton Knee Joint passer-by / non-user misuse - (add description)	mechanical : pinch point Passerby pinched by joint when inserting hand in mechanism	S1 Minor E0 Prevented A1 Likely	Negligible	Ensure passerby remain 2 feet away from joint at all times. /CS-01 - Low Risk	S1 Minor E0 Prevented A1 Likely	Negligible	On-going [Daily] User/Engineer/Tester
1-2-3-3	Exoskeleton Knee Joint passer-by / non-user misuse - (add description)	mechanical : sharp edges Passerby cut by sharp edges of joint when inserting hand/body part near or in mechanism	S2 Moderate E0 Prevented A1 Likely	Low	Ensure passerby remain 2 feet away from joint at all times. /CS-04 - Monitor	S2 Moderate E0 Prevented A1 Likely	Low	On-going [Daily] User/Engineer/Tester
1-3-1-1	Exoskeleton Knee Joint End User Enter/Exit Exoskeleton	mechanical : pinch point User pinched while attaching joint to leg	S1 Minor E1 Low Exposure A1 Likely	Negligible	Label and be aware of potential pinch locations; wear thick-layered pants. /CS-01 - Low Risk	S1 Minor E0 Prevented A1 Likely	Negligible	In-process User
1-3-1-2	Exoskeleton Knee Joint End User Enter/Exit Exoskeleton	mechanical : sharp edges User cut by sharp edges during attachment	S1 Minor E1 Low Exposure A1 Likely	Negligible	Wear thick-layered pants and ensure users leg is not near any sharp edges /CS-01 - Low Risk	S1 Minor E0 Prevented A1 Likely	Negligible	On-going [Daily] User
1-3-2-1	Exoskeleton Knee Joint End User Control Joint/Exo Movement	mechanical : crushing If all stops fail, user leg could be crushed during movement	S3 Serious E2 High Exposure A1 Likely	High	Check control stops and hard stops to ensure are working properly before putting on user. /CS-03 - Stop	S3 Serious E0 Prevented A1 Likely	Low	On-going [Daily] User
1-3-2-2	Exoskeleton Knee Joint End User Control Joint/Exo Movement	mechanical : pinch point	S2 Moderate E1 Low Exposure A1 Likely	Medium	Ensure user has no skin/clothing near joint before connecting power /CS-04 - Monitor	S2 Moderate E0 Prevented A1 Likely	Low	On-going [Daily] User
1-3-2-3	Exoskeleton Knee Joint End User Control Joint/Exo Movement	slips / trips / falls : slip May slip while walking using knee joint	S2 Moderate E1 Low Exposure A1 Likely	Medium	Utilize crutches in the event of slip /CS-02 - Operate	S2 Moderate E0 Prevented A1 Likely	Low	TBD User
1-3-2-4	Exoskeleton Knee Joint End User Control Joint/Exo Movement	slips / trips / falls : trip May trip while walking using knee joint	S2 Moderate E1 Low Exposure A1 Likely	Medium	Utilize crutches in the event of exoskeleton trip /CS-02 - Operate	S2 Moderate E0 Prevented A1 Likely	Low	TBD User



Item Id	Sub-process / User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Avoidance	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Exposure Avoidance	Risk Level	Status / Responsible /Comments /Reference
1-3-2-5	Exoskeleton Knee Joint End User Control Joint/Exo Movement	slips / trips / falls : fall hazard from elevated work May fall while walking using knee joint	S2 Moderate E1 Low Exposure A1 Likely	Medium	Utilize crutches in the event of fall /CS-02 - Operate	S2 Moderate E0 Prevented A1 Likely	Low	TBD User
1-3-2-6	Exoskeleton Knee Joint End User Control Joint/Exo Movement	ergonomics / human factors : excessive force / exertion Knee joint actuation produces more force than expected on users knee	S3 Serious E1 Low Exposure A1 Likely	High	Check control stops and hard stops to ensure are working properly before putting on user. /CS-03 - Stop	S3 Serious E0 Prevented A1 Likely	Low	On-going [Daily] User
1-3-2-7	Exoskeleton Knee Joint End User Control Joint/Exo Movement	ergonomics / human factors : repetition Repetitive movement of knee joint may strain/stress users knee	S2 Moderate E1 Low Exposure A1 Likely	Medium	Utilize for 30 min increments, then check to ensure users knee is not impacted /CS-02 - Operate	S2 Moderate E0 Prevented A1 Likely	Low	TBD User
1-3-2-8	Exoskeleton Knee Joint End User Control Joint/Exo Movement	ergonomics / human factors : lifting / bending / twisting If exo knee joint out of alignment could bend or twist users knee incorrectly	S2 Moderate E1 Low Exposure A1 Likely	Medium	Check alignment of joint before putting on user and confirm is correct. /CS-04 - Monitor	S2 Moderate E0 Prevented A1 Likely	Low	On-going [Daily] User
1-3-2-9	Exoskeleton Knee Joint End User Control Joint/Exo Movement	heat / temperature : severe heat Linear actuator heats up more than expected	S1 Minor E0 Prevented A1 Likely	Negligible	Wear thick-layered pants to protect from heat (ideally jean material) /CS-01 - Low Risk	S1 Minor E0 Prevented A1 Likely	Negligible	On-going [Daily] User
1-3-2-10	Exoskeleton Knee Joint End User Control Joint/Exo Movement	noise / vibration : noise / sound levels > 80 dBA Sound level above 80dBA	S1 Minor E0 Prevented A1 Likely	Negligible	Wear ear protection during use /CS-01 - Low Risk	S1 Minor E0 Prevented A1 Likely	Negligible	On-going [Daily] User
1-3-2-11	Exoskeleton Knee Joint End User Control Joint/Exo Movement	noise / vibration : fatigue / material strength Joint fails during extended periods due to fatigue	S3 Serious E0 Prevented A1 Likely	Low	Ensure crutches are used in event components fail due to fatigue /CS-02 - Operate	S3 Serious E0 Prevented A1 Likely	Low	On-going [Daily] User



Item Id	Sub-process / User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Avoidance	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Exposure Avoidance	Risk Level	Status / Responsible /Comments /Reference
1-4-1-1	Exoskeleton Knee Joint maintenance personnel lubrication	slips / trips / falls : debris failure to police area	S1 Minor E2 High Exposure A1 Likely	Low	Clean area prior to doing work /CS-02 - Monitor [CS-01 - Low Risk, CS-02 - Operate, CS-03 - Stop]	S1 Minor E1 Low Exposure A1 Likely	Negligible	On-going [Daily] Maintenance personel/tester
1-4-1-2	Exoskeleton Knee Joint maintenance personnel lubrication	slips / trips / falls : slip/fall from height water spray	S2 Moderate E2 High Exposure A1 Likely	Medium	Ensure maintenance is done near a support stand (ie table) and clean all spills immediately /CS-02 - Operate	S2 Moderate E0 Prevented A1 Likely	Low	On-going [Daily] Maintenance personel/tester
1-4-1-3	Exoskeleton Knee Joint maintenance personnel lubrication	pinch points : between robot/user situational awarness failure	S2 Moderate E2 High Exposure A2 Not Likely	High	Ensure joint power is entirely disconnected /CS-03 - Stop	S2 Moderate E0 Prevented A1 Likely	Low	On-going [Daily] Maintenance personel/tester
1-4-1-4	Exoskeleton Knee Joint maintenance personnel lubrication	struck by/impact : Exo Knee Joint unexpected start up	S3 Serious E2 High Exposure A2 Not Likely	High	Ensure joint power is entirely disconnected /CS-03 - Stop	S3 Serious E0 Prevented A1 Likely	Low	On-going [Daily] Maintenance personel/tester
1-4-2-1	Exoskeleton Knee Joint maintenance personnel trouble-shooting / problem solving	mechanical : crushing Can have fingers/hands/etc. crushed in knee joint while trouble shooting	S3 Serious E0 Prevented A1 Likely	Low	Ensure joint power is entirely disconnected during maintenance /CS-04 - Monitor	S3 Serious E0 Prevented A1 Likely	Low	On-going [Daily] Maintenance personel/tester
1-4-2-2	Exoskeleton Knee Joint maintenance personnel trouble-shooting / problem solving	mechanical : pinch point Can have fingers/hands/etc. pinched in knee joint while trouble shooting	S2 Moderate E0 Prevented A1 Likely	Low	Label and be aware of potential pinch locations /CS-04 - Monitor	S2 Moderate E0 Prevented A1 Likely	Low	TBD Maintenance personel/tester
1-4-2-3	Exoskeleton Knee Joint maintenance personnel trouble-shooting / problem solving	mechanical : sharp edges Could be cut by potentially sharp edges	S1 Minor E0 Prevented A1 Likely	Negligible	Be aware of edges/corners of design; sand/grind/deburr edges /CS-01 - Low Risk	S1 Minor E0 Prevented A1 Likely	Negligible	TBD Maintenance personel/tester

Item Id	Sub-process / User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Avoidance	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Exposure Avoidance	Risk Level	Status / Responsible /Comments /Reference
1-4-2-4	Exoskeleton Knee Joint maintenance personnel trouble-shooting / problem solving	electrical / electronic : shorts / arcing / sparking Could short system while trouble shooting electrical system	S3 Serious E0 Prevented A1 Likely	Low	Ensure electronics are grounded and all connections correct /CS-04 - Monitor	S3 Serious E0 Prevented A1 Likely	Low	On-going [Daily] Maintenance personel/tester
1-4-2-5	Exoskeleton Knee Joint maintenance personnel trouble-shooting / problem solving	slips / trips / falls : debris failure to police area	S1 Minor E1 Low Exposure A1 Likely	Negligible	Clean area prior to doing work /CS-01 - Low Risk	S1 Minor E1 Low Exposure A1 Likely	Negligible	On-going [Daily] Maintenance personel/tester
1-4-2-6	Exoskeleton Knee Joint maintenance personnel trouble-shooting / problem solving	slips / trips / falls : slip/fall from height water spray	S2 Moderate E1 Low Exposure A1 Likely	Medium	Ensure area clean prior to work and supports nearby /CS-04 - Monitor	S2 Moderate E0 Prevented A1 Likely	Low	On-going [Daily] Maintenance personel/tester
1-4-2-7	Exoskeleton Knee Joint maintenance personnel trouble-shooting / problem solving	pinch points : between robot/user situational awarness	S2 Moderate E1 Low Exposure A2 Not Likely	Medium	Lockout exoskeleton power /CS-04 - Monitor	S2 Moderate E0 Prevented A1 Likely	Low	On-going [Daily] Maintenance personel/tester
1-4-2-8	Exoskeleton Knee Joint maintenance personnel trouble-shooting / problem solving	struck by/impact : Exo Knee Joint unexpected start up	S3 Serious E1 Low Exposure A2 Not Likely	High	Lockout exoskeleton power /CS-04 - Monitor	S3 Serious E0 Prevented A1 Likely	Low	On-going [Daily] Maintenance personel/tester
1-4-3-1	Exoskeleton Knee Joint maintenance personnel preventative maintenance	slips / trips / falls : debris failure to police area	S1 Minor E1 Low Exposure A1 Likely	Negligible	Clean area prior to doing work /CS-01 - Low Risk	S1 Minor E1 Low Exposure A1 Likely	Negligible	On-going [Daily] Maintenance personel/tester
1-4-3-2	Exoskeleton Knee Joint maintenance personnel preventative maintenance	slips / trips / falls : slip/fall from height water spray	S2 Moderate E1 Low Exposure A1 Likely	Medium	Ensure area clean prior to work and supports nearby /CS-04 - Monitor	S2 Moderate E0 Prevented A1 Likely	Low	On-going [Daily] Maintenance personel/tester
1-4-3-3	Exoskeleton Knee Joint maintenance personnel preventative maintenance	noise / vibration : levels > 90 dba normal operational sound level	S2 Moderate E1 Low Exposure A3 Not Possible	Medium	Lockout all sources of energy. /CS-04 - Monitor	S1 Minor E0 Prevented A1 Likely	Negligible	On-going [Daily] Maintenance personel/tester

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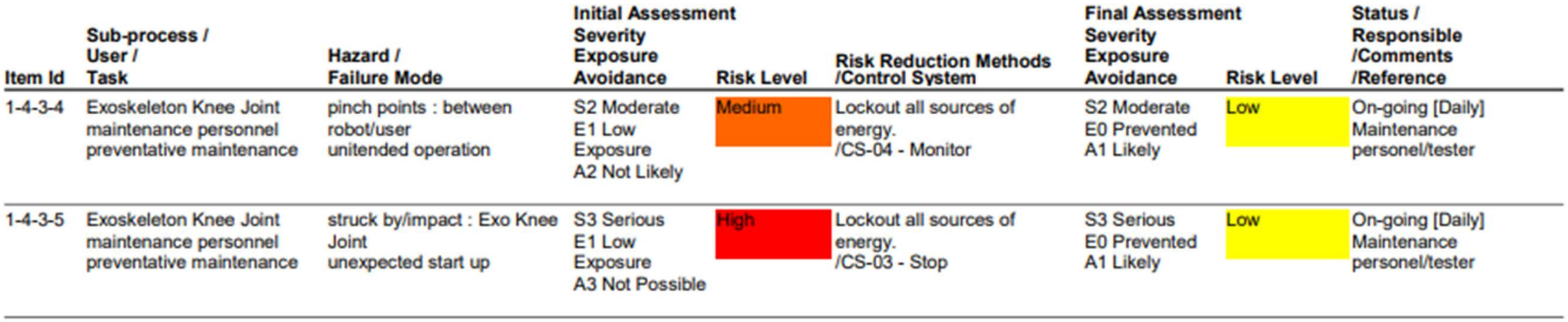
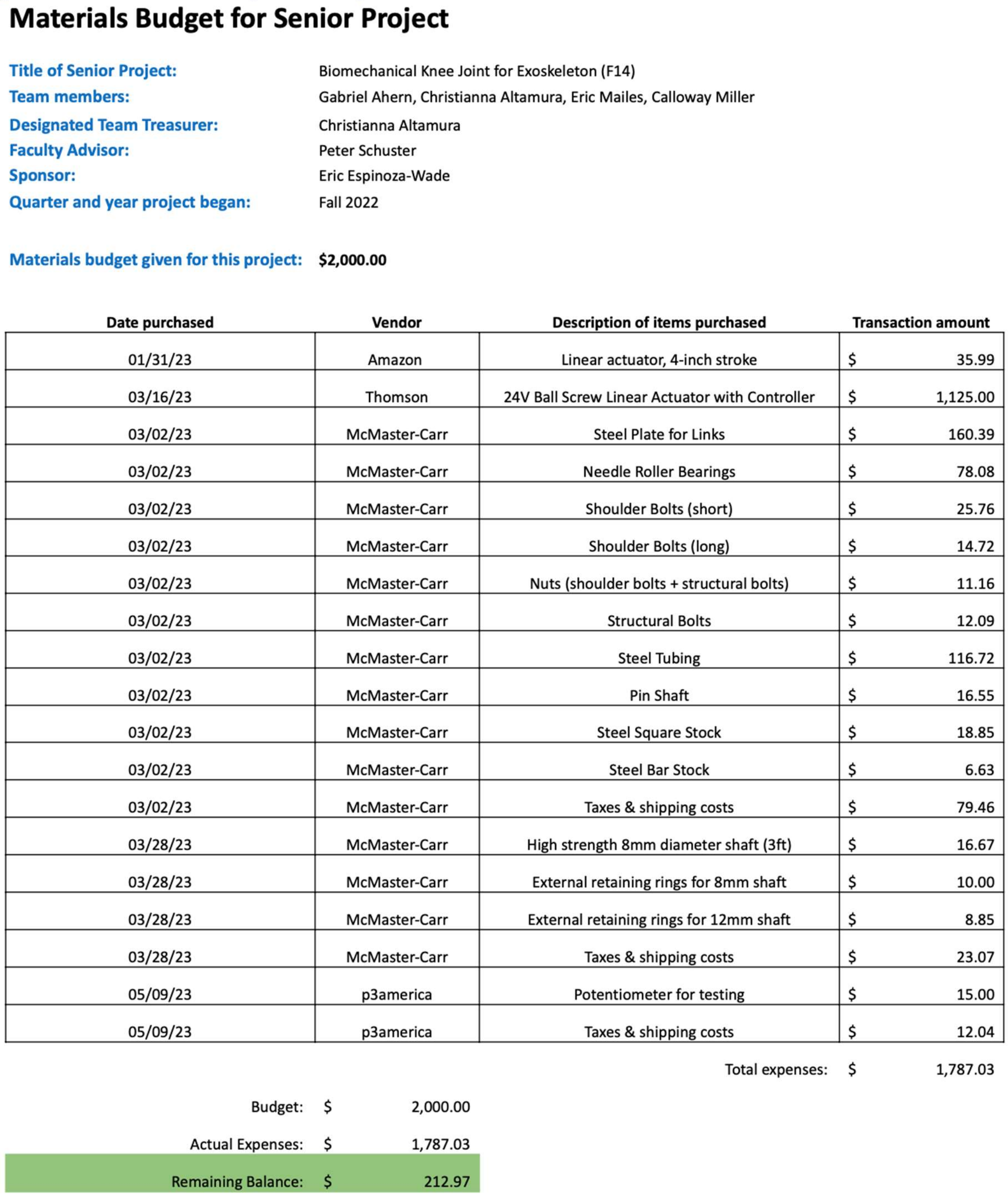
Privileged and Confidential Information



Item Id	Sub-process / User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Avoidance	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Exposure Avoidance	Risk Level	Status / Responsible /Comments /Reference
1-4-3-4	Exoskeleton Knee Joint maintenance personnel preventative maintenance	pinch points : between robot/user unitended operation	S2 Moderate E1 Low Exposure A2 Not Likely	Medium	Lockout all sources of energy. /CS-04 - Monitor	S2 Moderate E0 Prevented A1 Likely	Low	On-going [Daily] Maintenance personel/tester
1-4-3-5	Exoskeleton Knee Joint maintenance personnel preventative maintenance	struck by/impact : Exo Knee Joint unexpected start up	S3 Serious E1 Low Exposure A3 Not Possible	High	Lockout all sources of energy. /CS-03 - Stop	S3 Serious E0 Prevented A1 Likely	Low	On-going [Daily] Maintenance personel/tester

Figure 24. Risk assessment.

Appendix C – Final Project Budget



Materials Budget for Senior Project

Title of Senior Project: Biomechanical Knee Joint for Exoskeleton (F14)
Team members: Gabriel Ahern, Christianna Altamura, Eric Mailes, Calloway Miller
Designated Team Treasurer: Christianna Altamura
Faculty Advisor: Peter Schuster
Sponsor: Eric Espinoza-Wade
Quarter and year project began: Fall 2022

Materials budget given for this project: **$2,000.00**

Date purchased	Vendor	Description of items purchased	Transaction amount
01/31/23	Amazon	Linear actuator, 4-inch stroke	$ 35.99
03/16/23	Thomson	24V Ball Screw Linear Actuator with Controller	$ 1,125.00
03/02/23	McMaster-Carr	Steel Plate for Links	$ 160.39
03/02/23	McMaster-Carr	Needle Roller Bearings	$ 78.08
03/02/23	McMaster-Carr	Shoulder Bolts (short)	$ 25.76
03/02/23	McMaster-Carr	Shoulder Bolts (long)	$ 14.72
03/02/23	McMaster-Carr	Nuts (shoulder bolts + structural bolts)	$ 11.16
03/02/23	McMaster-Carr	Structural Bolts	$ 12.09
03/02/23	McMaster-Carr	Steel Tubing	$ 116.72
03/02/23	McMaster-Carr	Pin Shaft	$ 16.55
03/02/23	McMaster-Carr	Steel Square Stock	$ 18.85
03/02/23	McMaster-Carr	Steel Bar Stock	$ 6.63
03/02/23	McMaster-Carr	Taxes & shipping costs	$ 79.46
03/28/23	McMaster-Carr	High strength 8mm diameter shaft (3ft)	$ 16.67
03/28/23	McMaster-Carr	External retaining rings for 8mm shaft	$ 10.00
03/28/23	McMaster-Carr	External retaining rings for 12mm shaft	$ 8.85
03/28/23	McMaster-Carr	Taxes & shipping costs	$ 23.07
05/09/23	p3america	Potentiometer for testing	$ 15.00
05/09/23	p3america	Taxes & shipping costs	$ 12.04
		Total expenses:	$ 1,787.03

Budget:	$ 2,000.00
Actual Expenses:	$ 1,787.03
Remaining Balance:	$ 212.97

Figure 25. Final project budget including all expenses.

Appendix D – Design Verification Plan & Report (DVPR)

DVP&R - Design Verification Plan (& Report)											
Project:	F14; Iron Man Fan Girls	Sponsor:	LLEAP & Dr. Espinoza-Wade							Edit Date:	5/1/2023
TEST PLAN										TEST RESULTS	
Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING		Numerical Results	Notes on Testing
								Start date	Finish date		
1	Weight	Inspection	Weight	<15lb	Scale	Final knee joint prototype	Christie	5/8/2023	5/16/2023	FAIL: The prototype weighs 20.64 lb	The weight goal was not met. The linear actuator weighs much more than initially anticipated (roughly 14 lb), making up most of the weight of the prototype
2	Integration with Exoskeleton	Integrates with soft goods and linkages senior project teams	Pass/Fail	Fits without modification	TECHE lab, completed exoskeleton from club.	Final knee joint prototype	Cal	5/8/2023	5/30/2023	PASSED: No numerical Results	Exoskeleton fit with hip joint, linkages, and ankle joint components from LLEAP correctly.
3	Load Carrying Capability	Does not fail due to expected static loads	Pass/Fail	No visible deflection or breaks occured during or after testing.	TECHE Lab, power source, Test Stand, velocity sensor, weights	Final knee joint prototype	Eric	5/30/2023	5/30/2023	PASSED: Lifted 100lb, equating to roughly 1700 in-lbf or 192 N-m of torque	Tested up to 100lbs. Was able to raise weight with no issues (no reduction in speed, no increase in loudness, no increase in heat, etc.)
4	Control of Range of Motion	Able to stop even if power is cut at any point in actuation and fullextension (180 degrees) and flexion (90 degrees) possible	Pass/Fail	Knee Joint stops and holds movement when power cut, and is able to move from 90 to 180 degrees for full extension and flexion	Battery/power source. TECHE Lab	Final knee joint prototype, ESP 32, potentiometer, 3D printed sensor mount, test stand	Gabe	4/15/2023	5/31/2023	PASSED: Percent error was found to be 3.02% in the max case with an uncertainty of 2.95%	Was able to stop any time power was cut. Were able to get full range of motion with soft (code) stops at 93 and 175 degrees. Are able to control movement through various ways (bluetooth by sending 'Extend', 'Retract', 'Stop', 'Home') or by specifying an angle to go to on computer. Found uncertainty to be comprable in power to percent error. This is most likely due to noise in the wiring of the potentiometer, as well as a potentiometer that's not as accurate as the situation might necessitate, and the difficulties with lining up a protractor along an awkward angle.
5	Cost	Inspection	Pass/Fail	<$2000 total	N/A	Total parts and materials needed for all prototypes	Christie	4/8/2023	5/16/2023	PASSED: Final cost is $1870.55, which is $129.45 below budget	After acquiring a discount on the linear actuator, we were able to come in under budget for the project.
6	Manufacturable	Inspection	Pass/Fail	>70% of custom components must be made here at Cal Poly	Mustang 60, Aero Hangar, TechE labs: (CNC/manual mills, waterjetc, grinder, etc.)	All prototypes and their manufacturable components	Eric	4/8/2023	5/16/2023	PASSED: The prototype was successfully manufactured in-house at Cal Poly	All manufactured components were completed in the Cal Poly Machine Shops. Shown in the PDR, the manufacturing plan was closely followed, with a few minor changes being made. Shown in design changes section of the FDR, stress concentration relief replaced the radius of the aluminum coupler. Design changes were made as adjacent exoskeleton components design changed, such as the femur connection to the hip.
7	Device wearability	Sufficient clearance between top of prototype and user's hip to allow for powered hip joint connection	Distance/offset width	There is at least 2 inches of clearance between the top of the prototype and the user's hip	Ruler/Tape Measure, potential user	Structural prototype and/or Final prototype	Gabe	4/15/2023	5/23/2023	PASSED: There is 2 inches of clearance between the top of the prototype and Carlo Ruggiero's hip	The device wearability test was completed and acceptable results were achieved.
8	Loudness	Less than 70 dB	Decibels/noise	<70 dB while running	Sound sensor/application	Linear Actuator (from/for final prototype)	Eric	4/15/2023	5/30/2023	FAIL: Readings of 75dB	Found readings to be at 75 dB which is a failed criteria. However, our initial inspection criteria was based on a poor understanding of sound levels; while this fails the initially chosen inspection, a loudness level of 75 dB for short bursts is not a poor value.
NOTE:	Orange represents tests that were not necessary/done.										

Figure 26. DVP&R shows planned tests and inspections for prototype.

Appendix E – Test Procedures

Test Name: Integration with Exoskeleton (Test #2)

Purpose: The purpose of this test is to determine whether our designed knee joint fits into the exoskeleton being designed by LLEAP (to be fabricated before the end of Spring quarter) and, if not, by how much does it not fit (i.e., how much modification of their exoskeleton or our joint is necessary).

Scope: This test determines how well our knee joint fits with the exoskeleton design by LLEAP.

Equipment:

- Completed final prototype of knee joint from senior project team.
- Complete linkage connections/exoskeleton structure from LLEAP
- Complete hip structure from LLEAP
- Complete soft connections (connection points to user) by LLEAP
- Caliper(s)
- Protractors/angle measurement tools
- Tools/hardware for connecting (wrenches, Allen keys, etc.)
- Power tools (potentially for assembly)
- Exoskeleton mount structure from LLEAP (structure to hold complete exoskeleton without being put on user)

Hazards:

- Pinch points from connections (while connecting)
- Potential for sharp edges/corners (i.e., cuts)
- Heavy components (potential for components to be dropped on feet, hands, etc.)

PPE Requirements:

- Closed toe shoes
- If power tools necessary for assembly:
    - Safety glasses
    - Pants

Facility: 192-130 (TECHE Lab)

Procedure:

1) (If not completed by LLEAP) check assemblies of linkages, hip, and soft goods structures and confirm they are connected correctly.

2) Check assembly of knee joint and ensure all components are properly connected. Ensure that the linear actuator generates the correct movement with no issues.

3) Connect to the linkage structure.

4) Ensure all connections to linkages are secure and yield the correct configuration. If assembly is correct, leave components connected.

5) If components are not connected correctly, measure and record the degree of misconnection and take a picture of the connection. Then remove the structure.

6) Repeat steps 3 through 5 with hip and soft goods structures.

Results:

Table 2. Integration results for knee with rest of exoskeleton.

Structure to Connect:	**Pass/Fail (Connections correct or not):**
Linkages	Pass
Hip	Pass
Soft goods	Pass

Test Date(s): 5/30/22

Test Results: All components were properly connected. There were no notable misconnections.

Performed: Gabriel Ahern

Test Name: Prototype Carrying Capacity (Test #3)

Purpose:

This test will determine if the prototype can withstand the expected loads and evaluate whether it passes our design requirements.

Scope:

This test will focus on just vertical loads on the prototype applied at the hip to simulate loading conditions. It will not primarily consider side loading, but some unintended horizontal loading could occur.

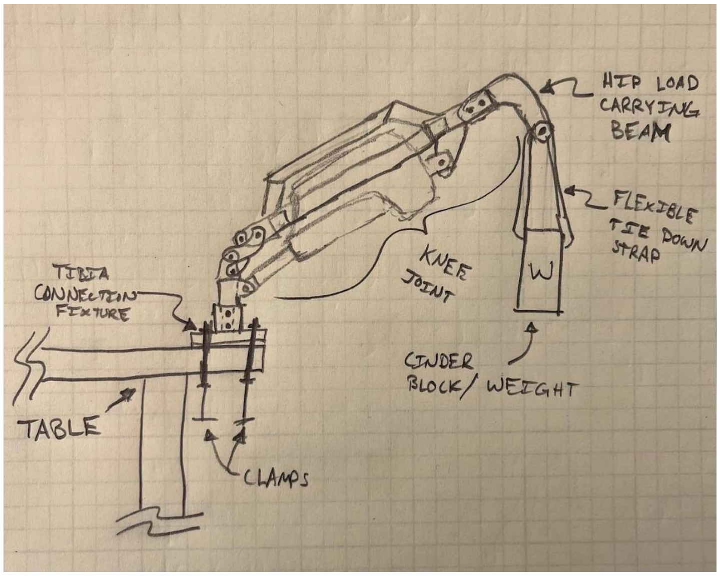


Figure 27. Schematic of load carrying capacity setup.

Equipment:

- Aluminum blocks (weight accessible to us in the TECHE lab)
- Tibia connection fixture
- Hip load carrying beam
- Hand-held scale

Hazards:

- Crushing hazard
- Electrical hazard (motor)
- Pinching hazard

PPE Requirements:

- Safety glasses and perform test with caution of listed hazards.
- Close toed shoes

Facility:

TECHE Lab

Procedure:

1. Ensure all individuals are wearing safety glasses and close toed shoes
2. Attach the test stand to a solid table
3. Clamp the tibia linkage to the test stand
4. Attach the knee joint to the tibia linkage using the aluminum coupler
5. Using the hand-held scale, load the bucket until the weight reaches 25 lb
6. Ensure no one's hand or feet are near pinch points and students are standing 2 feet away from the suspended bucket.
7. Actuate the knee joint until it reaches full extension.
8. Repeat this test for 50 lb, 75 lb, and 100 lb.

Results:

If the prototype can withstand the applied load, then it passes the test. If the prototype fails/breaks, then it fails the test. There is some uncertainty with the applied effective moment that can be calculated by combining the uncertainty of the weight with the uncertainty of the lever arm length to calculate the effective moment and the resulting uncertainty.

Test Date: May 30th, 2023

Test Results:

The knee joint was able to extend the knee with 25 lb, 50 lb, 75 lb, and 100 lb suspended 17 inches away from the joint center of rotation. These weights at those distances result in torques of 48 Nm, 96 Nm, 144 Nm, 192 Nm. The linear actuator was supplied with 24V and a maximum current limit of 10A. The load carrying capacity of the knee joint has been confirmed.

Table 3. Load carrying capacity test results.

Weight (lbf)	Pass/Fail
25.04	Pass
50.14	Pass
73.04	Pass
100.12	Pass

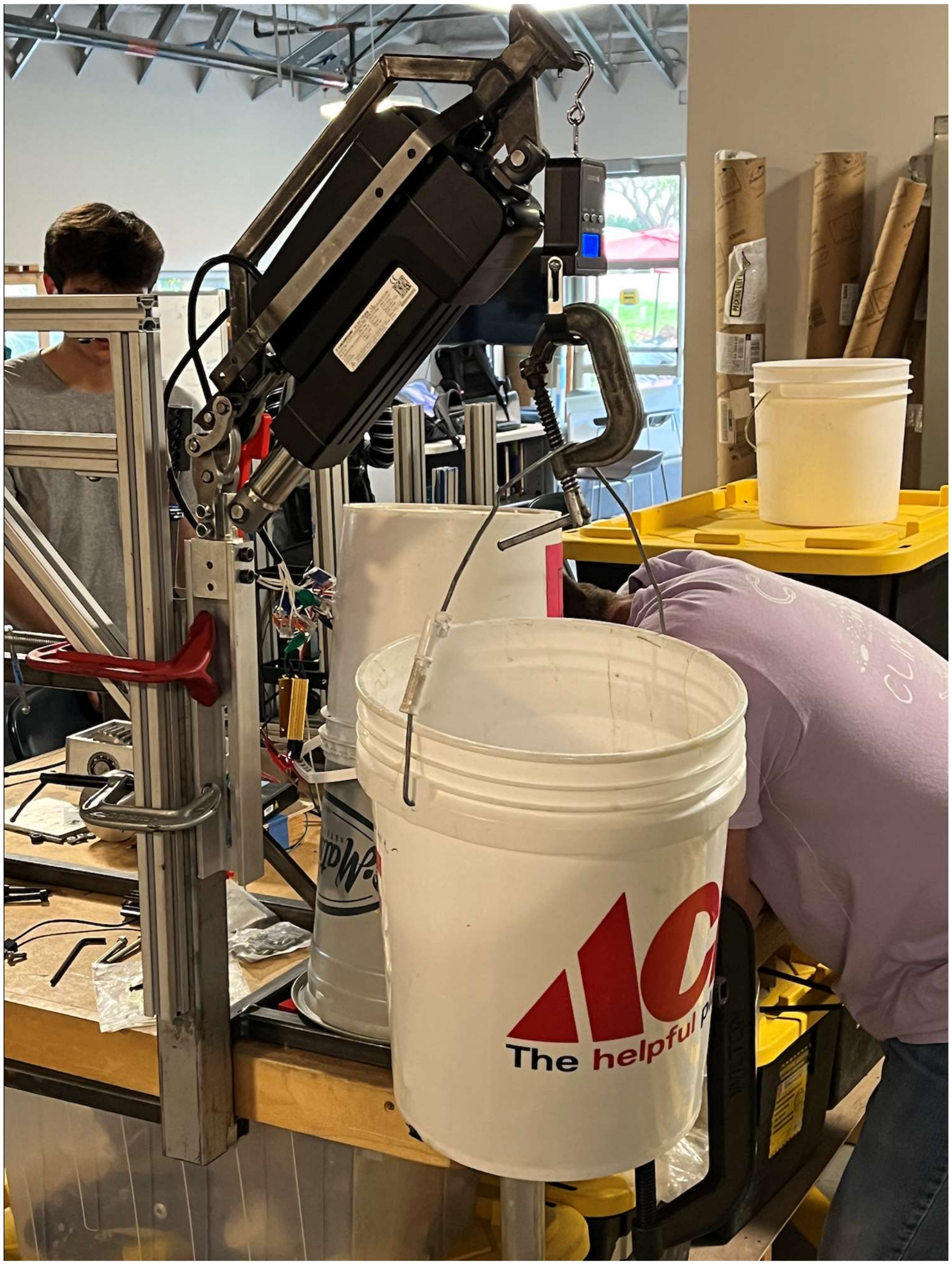


Figure 28. Load carrying capacity test setup.

Performed By: Cal Miller

Test Name: Control of Range of Motion (Test #4)

Purpose:

To ensure the knee joint is moving at the correct desired angle throughout full range of motion.

Scope:

This experiment tests the joint range of motion and control of the joint for an input from the linear actuator. This will test the accuracy of our kinematic simulation and determine whether we can achieve the expected output angular positions.

Equipment:

- Potentiometer
- ESP 32 circuit board
- 3D-printed sensor mount
- Complete prototype
- Test stand

Hazards:

- Pinching with the ACL and PCL components of the linkage
- Electric shock
- Falling prototype

PPE Requirements:

- Safety glasses

Facility: 192-130 (TECHE Lab)

Procedure:

1. Attach joint to the test stand
2. Assemble potentiometer mount
3. Fix potentiometer mount to the joint
4. Connect potentiometer to circuit board and start reading angle values
    1. Connect ESP 32 to a computer and read the relative voltage to calibrate the angle reading.
5. Record initial value for potentiometer and make sure reading is stable
6. Apply constant voltage to the linear actuator and start recording position data
7. Record data every 0.01 seconds and save it to a CSV file
8. Wait until joint is fully extended, then stop the actuator and cease data acquisition
9. Reset the joint to the retracted position and repeat steps 4-8 again
10. Find the difference between two subsequent recorded angular positions and divide by the time step to obtain the approximate angular velocity (finite difference method)

11. Plot the calculated angular velocity versus time and compare to the simulation
12. Perform uncertainty propagation to calculate the angular velocity uncertainty using the uncertainty of the potentiometer and the finite difference method equation

Results:

Pass Criteria:

Measured angular velocity is within 5% of the simulated angular velocity over time

Fail Criteria:

Measured angular velocity is not within 5% of the simulated angular velocity over time

Number of Samples to Test:

1

Design Analysis Equations/Spreadsheet

$$uncertainty = \pm\sqrt{\left(\frac{\partial P_{error}}{\partial \theta_{pot}} x\, u_{pot}\right)^2 + \left(\frac{\partial P_{error}}{\partial \theta_{phys}}\, x\, u_{physical}\right)^2}$$

Equation 1. Propogated uncertainty

$$P_{error} = abs\left|\frac{\theta_{phys} - \theta_{pot}}{\theta_{pot}} * 100\right|$$

Equation 2. Percent error

$$\frac{\partial P_{error}}{\partial \theta_{pot}} = -\frac{\theta_{phys}}{\theta_{pot}^2}$$

Equation 3. Partial derivative of percent error with respect to angular reading

$$\frac{\partial P_{error}}{\partial \theta_{phys}} = \frac{1}{\theta_{pot}}$$

Equation 4.

Test Date(s): May 31st

Test Results:

Performed By: Eric Mailes

Test Name: Comparable to Knee Size (Test #7)

Purpose: To compare the size of the linear actuator to the intended user in order to optimally attach to the user, ensuring the stroke length will not interfere with user's gait.

Scope: This test intends to analyze the device for wearability. The accuracy of this test must be within 0.5 inches of the actual measurement.

Equipment:

1. Ruler

Hazards:

1. Falling prototype

PPE Requirements:

- No PPE required, perform test with consideration of the listed hazards.

Facility: 192-130 (TECHE Lab)

Procedure: (List numbered steps of how to run the test, including steps for calibration, zero/tare, baseline tests, repeat tests. Can include sketches and/or pictures):

1) Hold the prototype up to the desired location of the joint with the knee at a 90° angle. Strap onto person using soft goods.

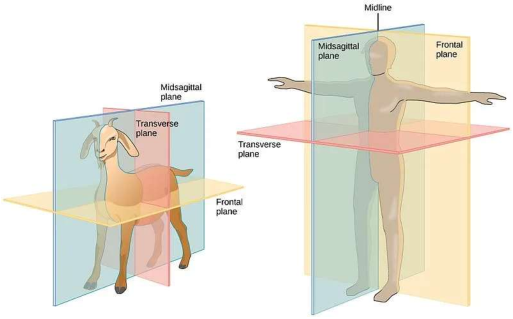


Figure 29. Sagittal plane.

2) Looking from the sagittal plane, measure the distance from the edge of the actuator to the edge of the user's thigh.

4) While the linear actuator is fully extended, measure the distance from the top edge of the linear actuator to the point of the hip.

Results: Pass Criteria, Fail Criteria, Number of samples to test, Design analysis equations/spreadsheet with uncertainty. Comment on how Uncertainty Analysis will be completed.

Pass Criteria:

1. The linear actuator's full stroke length does not reach the point of the hip when the four-bar linkage is centered on the knee.

Fail Criteria

1. The full stroke length protrudes past the point of the hip.

Test Date(s): May 26th

Test Results:

In order to test device wearability, we had an individual of similar thigh length to our intended challenger put the suit on. There was 1 inch of clearance between the individual and the suit, as the currently integrated hip is much larger than the hip design that will be finished by the end of the year. Figure X shows the actuator attached to a person that's thigh length is within +/- 0.5 inches of the intended user.

Figure 30. Evaluation of stroke length in comparison to user.

Performed By: Christie Altamura

Test Name: Loudness Test (Test #8)

Purpose: This test will determine whether the knee joint prototype passes the loudness criterion.

Scope: This test is performed on the knee joint as a whole, but it is anticipated that the linear actuator will be the loudest component, so the scope can be narrowed to specifically the linear actuator.

Equipment:

- Completed verification prototype
- Weights to simulate weight of user/exoskeleton
- Smartphone with app for measuring decibels

Hazards:

- Potential high decibel noise
- Falling weights
- Electrical shock
- Pinch points

PPE Requirements:

- Safety glasses
- Earplugs (for initial test)
- Close toed shoes

Facility: 192-130 (TECHE Lab)

Procedure:

1. Set up knee joint on test stand.
2. Set up smartphone one foot away from the prototype (closest to linear actuator).
3. Open the decibel X app.
4. Run linear actuator, unloaded, at 24 V. As long as noise level is below 85 dB (low end for recommended hearing protection), ear plugs can be removed unless later noise levels surpass 85 dB.
5. Record highest decibel reading from unloaded test.
6. Load weights at 25%, 50%, 75%, and 100% of load, each at 24 V
7. Record highest decibel reading from each test.
8. Gather all data from all four tests.

Results: The prototype will pass this test if all decibel readings are below 70 dB. Depending on the extent to which the prototype may exceed this limit, hearing protection may be advised for later operation.

Test Date(s): May 30, 2023

Test Results:

Table 4. Loudness test results.

Voltage (V)	**Loudness, 0% load (dB)**	**Loudness, 25% load (dB)**	**Loudness, 50% load (dB)**	**Loudness, 75% load (dB)**	**Loudness, 100% load (dB)**
16	69	-	-	-	-
24	77	72	74	75	76
32	80	-	-	-	-

Performed By: Christie Altamura

Appendix F. Software/Control Code

```
/*
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Senior Project, Linear Actuator Controller
05/16/23
*/

#include "ActuatorControl.h"
#include <Arduino.h>
#include "BluetoothSerial.h"

#define USE_PIN
const char *pin = "8008";
String execute;
String device_name = "SweepTheLeg";
BluetoothSerial SerialBT;
#if !defined(CONFIG_BT_ENABLED) || !defined(CONFIG_BLUEDROID_ENABLED)
#error Bluetooth is not enabled! Please run `make menuconfig` to and enable it
#endif
#if !defined(CONFIG_BT_SPP_ENABLED)
#error Serial Bluetooth not available or not enabled. It is only available for the ESP32 chip.
#endif

#define pinRet 14 //These are flipped which is why writing high and low is working; transistors backwards
#define pinExt 12
#define pinAng 32
#define pinLen 1
#define pinExtStp 27

ActuatorControl Act(pinExt, pinRet, 115200, pinAng, pinLen, pinExtStp);
float desAng;
float curAng;
bool guy = true;

void setup() {
  // Serial monitor setup for printing
  Serial.begin(115200);
  //Turns switches for Actuator off initially
  Act.Stop();
  //Setting up Bluetooth
  SerialBT.begin(device_name);
  Serial.printf("\"%s\" is started.\nPair it with Bluetooth!\n", device_name.c_str());
  #ifdef USE_PIN
    SerialBT.setPin(pin);
    Serial.println("Using PIN");
```

```
  #endif
}

void loop() {
  // Read received messages (Knee Joint Control) and store
  if (SerialBT.available()){
    char phoneChar = SerialBT.read();
    if (phoneChar != '\n'){
      execute += String(phoneChar);
    }else{
      execute = "";
    }
    Serial.write(phoneChar);
  }

  curAng = Act.AngMeas();

  // Check received message and control output accordingly
  if (execute == "Stop" || execute == "S" || execute == "s"){
    Act.Stop();
  }else if (execute =="Extend" || execute == "extend"){
    Act.Extend()
    //below commented out code details integration of softstops into bluetooth commands
   /* while(softStops(curAng) == false){
      Act.Extend();
    }
    Act.Stop();
    SerialBT.write("Softstop Reached. Went Home.")*/
  }else if(execute == "Retract" || execute == "retract"){
    Act.Retract();
  }else if(execute == "getAngle"){
    SerialBT.print("Current angle is: "); //might not work since a float
    SerialBT.println(Act.AngMeas());
  }else if(execute == "home" || execute == "Home"){
    Act.goHome();
  }

//This section details the use of serial for P-controller
 /* Serial.println(Act.AngMeas());
  if(Serial.available()>0){
    desAng = Serial.parseFloat();
    Serial.println(desAng);
    curAng = Act.goAngle(desAng);
    Serial.println(curAng);
    delay(10);
```

```
  }*/
  delay(10);
}
```

Figure 31. Main code for actuator control.

```
#include <Arduino.h>
#include "ActuatorControl.h"

int _pinAng;
int _pinExt;
int _pinLin;
int _pinRet;
int _pinExtStp;
bool Ret;
bool Ext;
int _baud;

ActuatorControl::ActuatorControl(int pinExt, int pinRet, int baudrate, int pinAng, int pinLin, int pinExtStp){
// setup Analogue to Digital Converter pin for input
  pinMode(pinExt,OUTPUT);
  pinMode(pinRet,OUTPUT);
  pinMode(pinAng,INPUT);
  pinMode(pinLin,INPUT);
  pinMode(pinExtStp,OUTPUT);

  _pinExt = pinExt;
  _pinRet = pinRet;
  _pinAng = pinAng;
  _pinLin = pinLin;
  _pinExtStp = pinExtStp;

  // Serial monitor setup for receiving/printing input (115200)
  _baud = baudrate;
}

void ActuatorControl::LinMeas(){
//This is a currently outdated method originally created to determine the distance measured by a linear
potentiometer connected to the
//linear actuator. Was scrapped when speed control became impossible (due to chosen Linear Actuator)
  int Volt = analogRead(_pinLin);
  float Klm = 1.0; //Gain for Linear Pot Calibration
  float Length = (Klm)*Volt*(109.0)*(1/4095.0);

  //prints Angle to serial monitor
```

```
  Serial.print("Length is: ");
  Serial.println(Length, 3);
}

float ActuatorControl::AngMeas(){
//This method returns the current angle reading from the potentiometer
  int Volt = analogRead(_pinAng);
  float Kam = 1.0; //Gain for Angular Pot Calibration
  float Km = 1.0; //Gain for Motor (Linear distance calibration)
  float Angle = (Km*Kam)*Volt*(360.0)*(1/4095.0) + 10;  //Not actually at 90
  return Angle;
}

void ActuatorControl::Extend(){
//This method extends the linear actuator.
  digitalWrite(_pinRet, LOW);
  digitalWrite(_pinExt, HIGH);
  Ext = true;
  Ret = false;
}

void ActuatorControl::Retract(){
//This method retracts the linear actuator
  digitalWrite(_pinExt, LOW);
  digitalWrite(_pinRet, HIGH);
  Ret = true;
  Ext = false;
}

bool ActuatorControl::softStops(float curAng){
//This method creates coded softStops/limits for the knee joint and can be called in other methods.
  float extBound = 173.0;
  float retBound = 93.0;

  if((curAng>=extBound) || (curAng<=retBound)){
    //Stop();
    goHome();
    return true;
  } else{
    return false;
  }
}

float ActuatorControl::accAngle(float curAng, float curAng2){
//This method can be used in other methods to filter out 'noise' angles from the potentiometer and system.
```

```
  if(curAng2>=(15+curAng) || curAng2<=(curAng-15)){
        curAng = curAng;
      }else if((Ext == true) && (curAng2<curAng)){
        curAng = curAng;
      }else if((Ret == true) && (curAng2>curAng)){
        curAng = curAng;
      }else{
        curAng = curAng2;
      }
      return curAng;
}

void ActuatorControl::goHome(){
//This method sends the actuator to a designated 'Home' position. Currently, that is fully retracted.
  Serial.begin(_baud);
  Serial.println("Soft stop hit. Going home.");
  float curAng = AngMeas();
  bool check = goodRange(95.0);

    while(check == false){
      if(95.0>curAng){
        Extend();
      }else if(95.0<curAng){
        Retract();
      }
      float curAng2 = AngMeas();
      if(curAng2>=(15+curAng) || curAng2<=(curAng-15)){
        curAng = curAng;
      }else if((Ext == true) && (curAng2<curAng)){
        curAng = curAng;
      }else if((Ret == true) && (curAng2>curAng)){
        curAng = curAng;
      }else{
        curAng = curAng2;
      }
      check = goodRange(95.0);
      delay(10);
    }
    Stop();
}

float ActuatorControl::goAngle(float desAng){
//This method accepts a desired angle input, compares it to the current angle, and moves the actuator accordingly. Continues to do so
//until the desired angle is reached and within the specified tolerance of the goodRange method.
```

```
    float curAng = AngMeas();
    bool check = goodRange(desAng);

    while(check == false){
      if(desAng>curAng){
        Extend();
      }else if(desAng<curAng){
        Retract();
      }
      //checks next Ang Position and esures not an outlier value (caused by pot. Noise)
      float curAng2 = AngMeas();
      if(curAng2>=(15+curAng) || curAng2<=(curAng-15)){
        curAng = curAng;
      }else if((Ext == true) && (curAng2<curAng)){
        curAng = curAng;
      }else if((Ret == true) && (curAng2>curAng)){
        curAng = curAng;
      }else{
        curAng = curAng2;
      }
      check = goodRange(desAng);

      if(softStops(curAng) == true){
       break;
      }

      delay(10);
    }
    Stop();
    return curAng;
    }

bool ActuatorControl::goodRange(float desAng){
  //This method accepts the desired angle and current angle and determines a good range of values for actuator to stop at.
  //Range is 1% of desired value
  float curAng = AngMeas();
  float UpTol = (desAng*.005) + desAng;
  float LowTol = desAng - (desAng*.005);

  //Checks if current angle is between upper and lower bounds of desired angle tolerance. If so, return true, if not, return false
  if(curAng>=LowTol && curAng<=UpTol){
    return true;
  }else{
```

```
    return false;
  }
  Serial.println(UpTol);
  Serial.println(LowTol);
}

void ActuatorControl::Stop(){
  digitalWrite(_pinRet, HIGH);
  digitalWrite(_pinExt, HIGH);
  Ret = false;
  Ext = false;
  //digitalWrite(_pinExtStp, HIGH);
}
```

Figure 32. Actuator control class code, cpp file.

```
#ifndef ActuatorControl_h
#define ActuatorControl_h
#include "Arduino.h"
class ActuatorControl{
public:
  ActuatorControl(int pinExt, int pinRet, int baudrate, int pinAng, int pinLin, int pinExtStp);
  void LinMeas();
  float AngMeas();
  void Extend();
  void Retract();
  bool softStops(float curAng);
  void goHome();
  float goAngle(float desAng);
  bool goodRange(float desAng);
  void Stop();
  float accAngle(float curAng, float curAng2);
  int _pinExt;
  int _pinRet;
  int _pinAng;
  int _pinLin;
  int _pinExtStp;
  bool Ret;
  bool Ext;
  int _baud;

private:
};
#endif
```

Figure 33. Actuator control class code, h file.

Appendix G. Range of Motion Test Data

Table 5. Potentiometer data for range of motion test.

Actuator Position	Angle Pot. Reading	Angle Pot Avg	Precision uncertainty	Angle Pot Stdev	Total pot uncertainty	Phys. Angle Meas	Phys Angle Avg
Fully Retracted	93.08	93.02	0.06	0.052	2.50	96	94.67
	92.99					94	
	92.99					94	
~1/4 Extended	105.65	105.82	0.17	0.15	2.51	108	108.33
	105.91					109	
	105.91					108	
~1/2 Extended	117.87	118.04	0.20	0.18	2.51	118	118.33
	118.22					119	
	118.04					118	
~3/4 Extended	135.19	135.25	0.11	0.098	2.50	141	139.33
	135.19					138	
	135.36					139	
Fully Extended	175.24	175.61	0.38	0.34	2.53	177	177.67
	175.89					178	
	175.71					178	

Table 6. Actuation uncertainty propagation with percent error and percent error uncertainty.

dPE/ dthetapot	dPE/ dpot*u^2	Precision uncertainty (u_stat)	Phys Stdev	Total phys uncertainty	dPE/ dthetaohys	dPE/ dphys*u^2	%Error	U_Perror
-0.0111	0.0008	1.3067	1.1547	2.8209	0.0107	0.0009	1.7702	4.1064
-0.0109	0.0007				0.0108	0.0009		4.0733
-0.0109	0.0007				0.0108	0.0009		4.0733
-0.0097	0.0006	0.6533	0.5774	2.5840	0.0095	0.0006	2.3719	3.4438
-0.0097	0.0006				0.0094	0.0006		3.4470
-0.0096	0.0006				0.0094	0.0006		3.4312
-0.0085	0.0005	0.6533	0.5774	2.5840	0.0085	0.0005	0.2457	3.0566
-0.0085	0.0005				0.0085	0.0005		3.0556
-0.0085	0.0005				0.0085	0.0005		3.0500
-0.0077	0.0004	1.7286	1.5275	3.0394	0.0074	0.0005	3.0216	2.9634
-0.0076	0.0004				0.0074	0.0005		2.9368
-0.0076	0.0004				0.0074	0.0005		2.9404
-0.0058	0.0002	0.6533	0.5774	2.5840	0.0057	0.0002	1.1692	2.0733
-0.0058	0.0002				0.0057	0.0002		2.0676
-0.0058	0.0002				0.0057	0.0002		2.0708